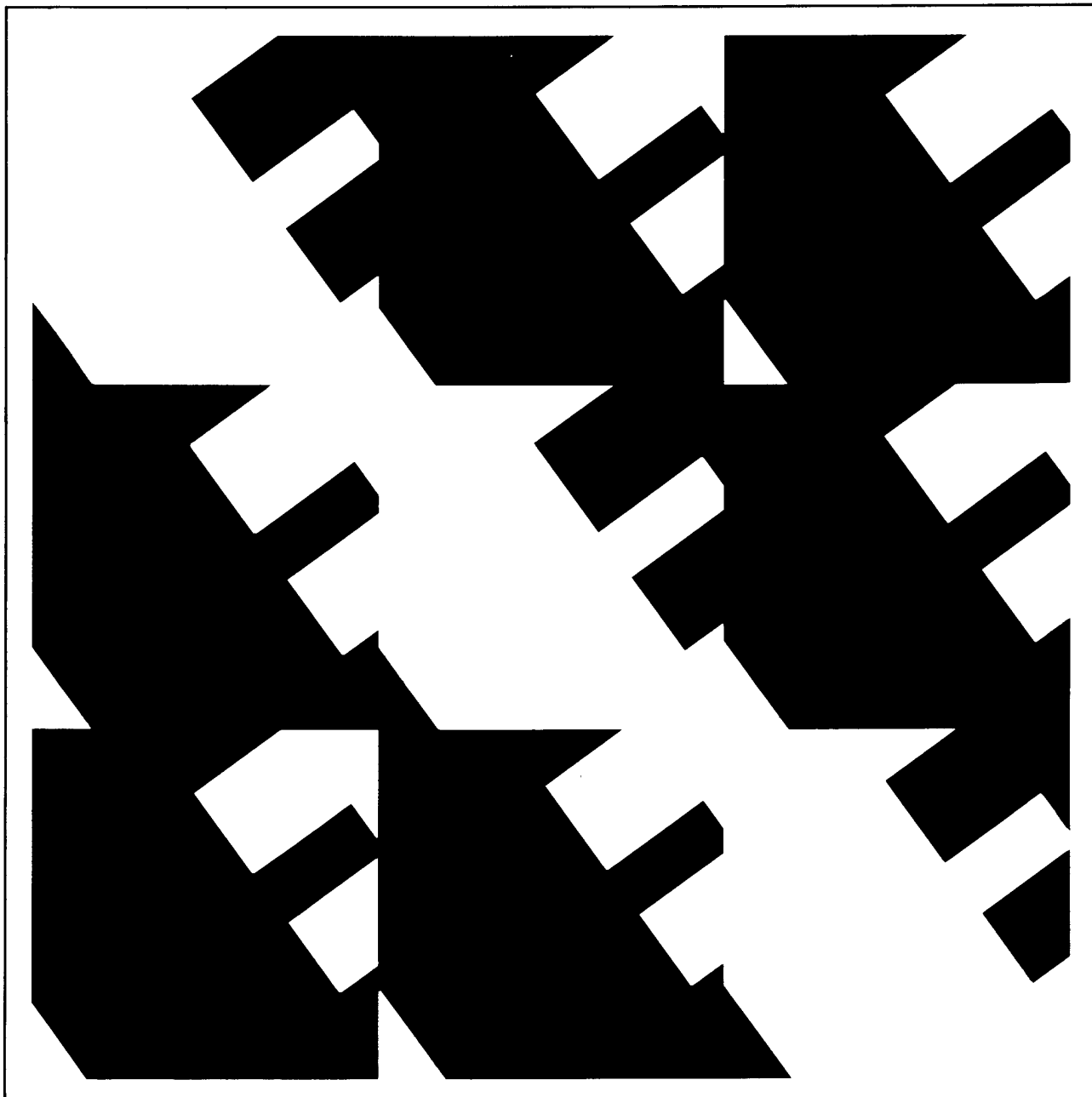


Master Test Code for Electrical Measurements in Power Circuits

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FOREWORD

At the suggestion of members of the Rotating Machinery Committee of the AIEE, the Instruments and Measurements Committee voted, in 1950, the appointment of a subcommittee for preparing a Master Test Code for Electrical Measurements in Power Circuits.

Part 6, Electrical Measurements, of the ASME Power Test Code Supplement on Instruments and Apparatus of 1934 served to form the basis for the new document. Material was also taken from AIEE Test Codes 502 on Single-Phase Motors and 503 on Synchronous Machines. Other codes of the AIEE were reviewed and much new material was added.

It should be noted that this code does not include all possible tests on electric apparatus or tests conducted for research purposes.

Throughout the development of this document excellent cooperation existed between AIEE and ASME at all levels of operation.

Subcommittee members who have served during all or part of the period from the initial appointments, in 1950, until the approval of the code by the Instruments and Measurements Committee in 1955, are,

C. J. Zeller, <i>Chairman</i> 1950-53	
J. H. Miller, <i>Chairman</i> 1953-55	
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Suggestions for improvement of this code will be welcomed. They should be sent to the Secretary of the AIEE Standards Committee, 33 West 39th Street, New York 18, N. Y.

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MASTER TEST CODE FOR ELECTRICAL MEASUREMENTS IN POWER CIRCUITS

GENERAL

- 1.10 Purpose**—It is the purpose of this code to give instructions for those measurements of electrical quantities which are commonly needed in determining the performance characteristics of electric machinery and equipment. The choice of method and instruments to be used in any given case depends on the purpose of the measurement, the accuracy required, the time and testing equipment available and the nature of the circuit to be measured.
- 1.20 Scope**—The methods given here include measurements, as made with either indicating or integrating instruments, of power, voltage and current in direct-current and alternating-current single-phase and polyphase rotating machinery, transformers, induction apparatus, arc and resistance heating equipment and mercury arc rectifiers. It also includes measurements made with supplementary instruments and devices. This code does not include such measurements as resistance and temperature which are often included in determining the performance characteristics of electric machinery. Instruments for these latter measurements will be found in the specific codes dealing with the particular measurement; such as, AIEE Master Test Code for Resistance Measurement, No. 550, and AIEE Master Test Code for Temperature Measurement, No. 551.
- 1.30 Units**—The measurement of any electrical quantity is the comparison of that quantity with another quantity of the same kind which has been chosen as a unit. The fundamental or basic electrical units are based on the meter-kilogram-second system of absolute units.
- 1.31 Practical Absolute Units**—The practical absolute units of the electrical quantities are:
- | | |
|-----------------------------------|---------------------|
| Electromotive Force and Potential | |
| Difference (Voltage) | volt |
| Resistance | ohm |
| Current | ampere |
| Quantity | coulomb |
| Power | watt |
| Energy | joule (watt-second) |
| Capacitance | farad |
| Inductance | henry |
- 1.32 Classes of Electric Measuring Instruments**—Measurements in the engineering field of the more usual electrical quantities, such as voltage, current, power and energy, are usually made with indicating, curve-drawing or integrating instruments. These are available in various forms which are generally classified as standard instruments, portable instruments and switchboard instruments. "Standard instru-

ments" are high-grade, high-accuracy, indicating instruments which, while more or less portable, are intended primarily for the laboratory. So-called "portable instruments" are somewhat less sensitive but are strictly portable and specially applicable to general testing work, particularly outside the laboratory. "Switchboard instruments" are designed for permanent mounting on switchboards along with the equipment by means of which electric apparatus is controlled. They have to withstand severe conditions, such as being in the circuit continuously and the vibration which may exist. Therefore, they are more sturdy and somewhat less accurate than the portable form.

Portable indicating instruments are the most suitable class and form for general testing of electric equipment. They have the best combination of the important characteristics of sturdiness, portability, accuracy, and reliability. Where measurements must be made over a long period of time and it is not feasible to make continuous observations of indicating instruments, curve-drawing instruments may be employed but with the sacrifice of some accuracy. Of course, in the measurement of integrated quantities such as ampere-hours and energy (kwhr), integrating instruments, usually called "meters" are employed, in which total quantity to any given instant is indicated on a dial register.

- 1.33 Instrument Specifications**—Reference is made to the American Standard for Electric Indicating Instruments, C39.1 - 1955, sponsored by the ASA Electrical Standards Board and prepared by a subcommittee representing both manufacturers and users of instruments. Both as to definitions and specific requirements, this standard is recommended to identify the particular types of instruments which should be used for power measurements. A study of the definitions will be of interest to those concerned with electrical measurements of high accuracy.
- 1.40 Range and Accuracy**—The range of measurements of voltage, current or power is almost unlimited because the judicious use of instruments of appropriate range used, if necessary, with auxiliary devices such as shunts, series resistors and instrument transformers permits great flexibility in range.
- 1.41 Limits of Error**—The limit of error of an electric indicating instrument is usually specified by the manufacturer as a percentage of full scale. This tolerance is applicable to an instrument in an "as received condition" or when used under reference conditions of temperature, humidity, position, etc. These conditions have been designated as influences in ASA C39.1 - 1955, American Standard for Electric Indicating Instruments. Where the instrument in use is subject to influences beyond those specified

as reference conditions, additional tolerances are permitted.

The accuracy obtainable in the measurement of an electrical quantity, as of any other quantity, depends upon various factors which enter into the determination, such as correctness of the method, constancy of the quantity being measured, condition of the instruments employed, number and magnitude of the unavoidable errors and correctness of the calculations. The following table indicates in a general way the accuracy of the final result which reasonably may be expected using portable instruments of the 1/4 of 1 percent accuracy class and switchboard instruments of the 1 percent accuracy class as defined in the American Standard C39.1 referred to above. The listing assumes average observers, testing electric apparatus under ordinary conditions, and with the use of such calibration corrections as may be included with the instrument. Where special care is taken by experienced observers, and the instruments are checked immediately before and after the test with application of the mean of the calibration corrections found, the errors may be reduced as much as 50 percent.

Quantity Measured and Instruments Used	Limits of error in percent of full-scale deflection, for self-contained instrument	Limits of error, in percent when used with auxiliary apparatus*
Voltage (Voltmeter)		
Portable, d-c	0.25	0.25 - 0.5
Portable, a-c	0.25	0.25 - 0.5
Switchboard, d-c	1.0	1.0 - 1.5
Switchboard, a-c	1.0	1.0 - 1.5
Curve drawing	1.5	1.5 - 2.0
Current (Ammeter)		
Portable, d-c	0.25	0.25 - 0.5
Portable, a-c	0.25	0.25 - 0.5
Switchboard, d-c	1.0	1.0 - 1.5
Switchboard, a-c	1.0	1.0 - 1.5
Curve drawing	1.5	1.5 - 2.0
Power (Wattmeter)		
Portable	0.25	0.25 - 0.75
Switchboard	1.0	1.0 - 1.5
Curve drawing	1.5	1.5 - 2.0
	Limits of error in percent of reading, for self-contained instrument	Limits of error, in percent when used with auxiliary apparatus
Energy (Watt-hour Meter)		
Direct Current	1.5	1.5 - 3.0
Alternating current, single phase	1.0	1.0 - 2.0
Alternating current, polyphase	1.0	1.0 - 2.0
	Limits of error in percent of actual scale range, for self-contained instrument	
Frequency (Frequency Meter)		
Portable	1.5	1.5
Switchboard	3.0	3.0

Quantity Measured and Instruments Used	Limits of error for self-contained instrument or when used with auxiliary apparatus
Power Factor (Power Factor Meter) (Portable) (Switchboard)	Within 0.02 (2 percent power factor) from 20 to 40 percent, inclusive; rated current, and within 0.01 from more than 40 up to and including 120 percent rated current for a scale length of 0.5 lagging to 0.5 leading, inclusive, with rated voltage and frequency applied.

1.42 Selection of Instruments—A test often represents considerable money value either because of a bonus or penalty dependent upon the results, or because of the investment in labor represented. The latter becomes a total loss if it is necessary to repeat the work owing to errors made in the test. It is evident that in such cases it is good economy to take great care in selecting the instruments to be used; and in any test, instruments should be chosen which are accurate and reliable so that the result obtained may be used with confidence. If possible the calibration record for several months back should be scrutinized; erratic performance or a recent change in calibration constitutes ground for rejection. The zero indication should be stable; there should be no signs of friction at any part of the scale; and operation at full load for a reasonable period of time should not alter the accuracy beyond the "Sustained Operation Influence" requirement of American Standard C39.1-1955 previously referenced. The ranges should be selected, if possible, so that the readings will be in the upper parts of the scales. In this respect, multiple-range instruments are especially desirable. It is preferable that the graduations of scales should be "open" throughout, that is, not unduly restricted at the ends, especially the lower end. The scale factors should be decimal multiples or numbers which make for easy computation.

1.43 Transportation of Instruments—Care should be taken that calibrated instruments are moved to the test positions from the laboratory without impairing their calibrations. If many instruments are to be transported considerable distances in a truck or car, it is well to use strong wooden boxes lined with heavy felt. The instruments should be placed upside down on cushions. This puts the pressure on the top bearing which serves as a guide bearing and lets the normal bottom bearing float and not be crushed. When instruments are carried by their handles, the weight of the moving system is usually removed from the pivot points. Instruments should be laid on the floor or table without jarring; a fall though a few inches may cause a conical pivot to produce sufficient stress to crack a jewel bearing. Certain instruments have means for taking the weight of the moving system off the lower bearing when not

*Auxiliary apparatus: shunts, multipliers, or instrument transformers.

**These values apply from 10 percent to 200 percent load current and from 1.00 to 0.50 power factor lagging.

in use. Care should be taken that this is done. Instrument transformers are best shipped in boxes separate from instruments.

- 1.50 Installation**—In testing electric apparatus, the set-up should be arranged in a neat and workmanlike manner.

The purpose of the test should be clearly understood and the proposed procedure carefully thought out and planned beforehand. Instruments should be placed on a firm steady non-magnetic table or bench, which is level, and switches conveniently located and the wiring neatly and logically arranged. Instruments and switches should be conveniently located to facilitate reading and to reduce the chance of errors due to manipulating the wrong switches.

- 1.51 Location in Circuit**—All measurements should be made at such points in the circuit that there will be no question as to the correctness of the results. That is, current connections for ammeters and wattmeters should be made at a point where the current is the same as at the machine or device terminals, while voltage connections should be made at the machine or device terminals or at a point sufficiently close so that the intervening voltage drop is negligible. In general all instrument connections should be made as near to the machine or device terminals as possible because all performance guarantees and data are usually given for measurements at the terminals.

The table or bench, on which the instruments are located should be placed within sight of the apparatus under test whenever feasible, so that the testing engineer can observe the operation of the machine at all times. (See also paragraph 1.60-1)

- 1.60 Precautions in Taking Readings**—The following precautions should be observed in setting up and using electric instruments for input or output measurements of electric apparatus:

(a) Indicating and curve-drawing instruments should be of such a range that the quantity being measured will produce a reasonably large deflection preferably more than half scale, as the observational error expressed in percent decreases in direct proportion to the increase in the magnitude of the deflection.

Integrating meters should be of such a range that the loads will come between 30 and 120 percent of the rated capacity of the meter.

(b) Reliance should not be placed on a single observation. When making direct measurements, such as voltage, more observations are required with a varying quantity than with a constant quantity, to give an average which is reasonably reliable. When making measurements for a derived quantity, such as resistance, observations should be made for several values of the quantities measured, thereby reducing the chance of accidental errors. For example, in measuring the resistance of a circuit by the fall-

of-potential method, the result of one observation of amperes and volts is not as reliable as the mean of several observations, each taken with a slightly different current, noting, however, that the accuracy increases only as the square root of the number of observations. Or if a resistance is measured with a bridge, the average of several measurements with different settings is usually more accurate than a single measurement.

(c) The possible presence of external or stray magnetic fields, both direct and alternating, should always be considered. Such fields may be produced by current in neighboring conductors or buses on switchboards, by certain electric machinery and apparatus and by structural iron and steel in buildings. These fields introduce errors by combining with the normal field of electric instruments and thus increase or decrease the deflection. Instruments should be selected conforming to American Standard C39.1 where magnetic field influence is limited to the best commonly accepted commercially obtainable values. Commercial indicating instruments are now usually equipped with magnetic shields but it is not safe to depend absolutely on them. The instrument should be placed as far as possible from any suspected source of stray fields. In the case of electrodynamic instruments the presence of a disturbing external field with a horizontal component may be detected by noting the change in indication when the connection of instrument leads is reversed. In the case of permanent-magnet instruments, the presence of a disturbing external field with a horizontal component may be detected by noting the change in the indication (assuming that the quantity measured and the field remain constant) when the instrument is turned through an angle of 180 degrees. In both cases, the average indication will be correct provided the difference is not over about 3 percent.

Where an instrument must be used in the presence of a disturbing stray field, it may be possible to shield it by placing the instrument in a wooden box lined and covered with laminations of soft sheet-iron or steel to a total thickness of $\frac{1}{4}$ to $\frac{1}{2}$ inch, with a suitable opening in the top for observing the pointer. The instrument should be calibrated in the box exactly as used in the test.

(d) Although many modern portable instruments of the usual types are magnetically shielded, they are often influenced by stray fields produced by wiring which is close to the instrument.

If the wiring cannot be arranged otherwise, the field produced should be reduced to a minimum by twisting together, for a distance of three or four feet from the instrument, the two conductors of each circuit carrying any appreciable current.

(e) To avoid possible errors due to stray magnetic fields from the instruments themselves, they should not be placed close together. A safe rule

is a distance of not less than 12 inches from center to center of adjacent instruments.

The secondary leads to voltage circuits should be kept close together to avoid induced voltages in secondary loops. Large currents at 60 cps or small ones at audio frequencies can cause large errors.

(f) Instruments with glass or hard-rubber covers should not be rubbed, especially with a dry cloth. The electrostatic charge thereby produced is often sufficient to change the deflection materially. If it should be necessary to rub the glass cover when readings are about to be taken, the electrostatic charge may be dissipated by breathing on the glass.

(g) Care should be taken that the introduction of instruments or other testing apparatus does not alter the quantities being measured or the circuit conditions. For example, the mistake has sometimes been made of using low-range instruments in the secondary circuit of a current transformer in order to secure a good deflection at light loads. It should be remembered that the impedance of otherwise identical ammeters or of the current coils of wattmeters varies inversely as the square of the rated current, so that the impedance of low-range instruments may be high enough to alter appreciably the ratio and phase angle of the current transformer.

(h) It is desirable, when feasible, to provide switches so that the instruments can be conveniently cut out of the circuit except when taken readings, provided this does not materially influence the quantities being measured. This reduces the danger of damage to instruments in case of trouble in the apparatus being tested and possible errors due to temperature changes and spring set in instruments not intended to be kept continuously in the circuit. Furthermore, a switch makes the quick substitution of another instrument convenient and safe.

Instrument switches in the secondary circuits of current transformers should be so arranged that the circuit is never opened when "alive", because of the high voltage which may be developed. (See also paragraph 4.40).

(i) Care should always be taken to see that all contacts are clean and that all connections are tight in order to avoid errors due to high contact resistance.

(j) When reading indicating instruments, it is desirable to tap the instrument gently to eliminate the effect of friction.

(k) Sufficient illumination should be provided so that instruments can be read easily, quickly and accurately.

(l) When making a test in a power station or similar place, obviously the instrument should be located where there is as much freedom as possible from vibration, magnetic or electrostatic fields, and abnormal temperatures. Where excessive vibration

cannot be avoided, the instruments should be placed on pads of sponge rubber, hair felt, or similar material.

(m) At voltages of 500 volts and greater, the electrostatic attraction between moving and fixed parts may become serious. This attraction will disappear if the two parts are at the same electrostatic potential. When grounding is permissible, this can be done by connecting the circuit to earth at the point where the instrument is connected, care being taken that the moving-coil end of the instrument is on the ground side. When the instrument must be used at a high potential difference to ground, it must be thoroughly insulated from the ground and the moving element connected to the case or to an electrostatic shield around the instrument. Such a connection is a source of danger and great care must be taken that the observer does not come into contact with the instrument or the shield. The latter may be conveniently made from ordinary iron-wire netting.

(n) In shunted ammeters, errors may arise from the unequal percentage increase of resistance for the shunt and the millivoltmeter, due to the passage of the current. In old instruments, with internal copper shunts, this error is pronounced. In precision ammeters this error is not troublesome.

In voltmeters, if they are kept in circuit, there will be heating of the series resistance and movable coil due to the passage of the current, but because of the low net temperature coefficient of direct-current instruments the resulting error will not be great. The energy dissipated at full-scale deflection is about 1.5 watts in some types.

In wattmeters and alternating-current voltmeters, together with their accompanying multipliers, much more heat must be dissipated—about 7 watts in a 150-volt instrument at full-scale deflection. In addition, the proportion of copper to zero-temperature-coefficient resistance wire is greater than in direct-current instruments. The liberation of so much heat in a confined space affects not only the resistances but the springs as well. The permanent state of temperature is attained gradually, and as a result there is a progressive change in the corrections when the instrument is left in the circuit. In all cases, high-resistance multipliers must be properly ventilated.

1.70 Corrections—The zero setting of the instrument should be observed before taking readings. If the instrument has no zero adjustor or if the adjustor is not accessible to the observer, the necessary correction must be applied to the observed reading. If the instrument is provided with a zero adjustor, the pointer can be set on the zero mark and the observed reading will then be correct, provided there are no other corrections to be applied. The zero setting may be affected by temperature changes

and by the position of the instrument and should therefore be checked before taking readings if either of these effects is subject to change. If the zero reading of an instrument is altered more than 0.5 to 1 mm by tipping the instrument 10 degrees in any direction from the normal (horizontal) position of use, the moving system is not well balanced and the instrument should be carefully leveled before using.

- 1.80 Calibration**—In all tests made under this Master Test Code the electric instruments for measuring voltage, current, power, and energy shall be calibrated before and after the test with as little lapse of time as feasible between the calibrations and the test. Calibrations shall be made with (a) secondary standards which have been certified by the National Bureau of Standards, or (b) with standardized instruments which have been calibrated with such standards and which are used for standardizing purposes only.

VOLTAGE MEASUREMENTS

- 2.10 Description**—Voltage measurements in connection with tests under this Master Test Code shall be made, in general, with portable indicating voltmeters. Switchboard instruments are not usually considered acceptable but if they are used, the calibration shall show the errors under the conditions of use, *i.e.*, as to position, temperature, distance from observers, etc.
- 2.20 Direct-Current Voltmeters**—A voltmeter for direct current is essentially a low-sensitivity portable galvanometer provided with a scale over which moves a pointer attached to the moving system. The scale is calibrated in volts by comparison with an indicating instrument of higher accuracy or by means of a potentiometer. Practically all direct-current voltmeters employ the principle of D'Arsonval galvanometers. They consist essentially of a light rectangular coil of fine wire wound upon an aluminum frame, pivoted in jeweled bearings and capable of rotating in the annular space between a core and pole pieces; a permanent magnet is arranged to produce a constant and uniform radial magnetic flux in the annular gap. The aluminum frame, being a closed secondary circuit, acts as a brake or damper while the coil is deflecting, thus quickly bringing the moving system to rest. A light tubular pointer attached to the coil moves over a graduated scale. The current is introduced into the coil by two spiral springs which also provide the controlling force. Since the field strength and the gradient of the controlling forces are uniform, the deflection is proportional to the current passing through the coil, and the scale divisions are uniform; in such a case the instrument is said to have an "evenly divided" scale. A resistor of high resistance is connected in series with the moving coil in order

that the small current required for full-scale deflection may flow when a given maximum voltage is applied. This resistor is known as the series resistor, and may be either installed in the instrument case or in an external case. A multiplier is a particular type of external series resistor which is used to extend the voltage range of an instrument beyond some particular value for which the instrument is already complete.

- 2.30 Alternating-Current Voltmeters** — Alternating-current voltmeters for engineering power tests at frequencies between 25 and 125 cycles per second are either the electrodynamic type or the soft-iron-vane type. Both of these types are made in the ordinary portable form but working standards, such as laboratory standards and precision voltmeters, are usually of the electrodynamic type. Electrodynamic type voltmeters can be used up to frequencies of 1000 cps provided they are compensated for such a frequency coverage or the frequency correction specified by the manufacturer is applied. At higher frequencies the reactance of the coils becomes dominating and introduces gross errors. Since the inductance of a soft-iron-vane voltmeter is not usually specified by the manufacturer, and may vary with frequency as well as scale deflection, frequency corrections are generally too involved to be readily applicable to this type. For making voltage measurements at frequencies above 125 cps frequency compensated voltmeters must be used. Some of the more common frequencies encountered in the extended range have been 180 cps for portable machine tools and high-speed motors, 400 and 800 cps for aircraft, 960 to 3000 cps for electric-furnace applications, and 8,000 to 12,000 cps for industrial heat-treatment use. Frequency-compensated voltmeters rated at 0-150 volts can be used for voltage measurements in the compensated range. Unfortunately, frequency compensation in low-range voltmeters requires large components and, therefore, low-range frequency compensated voltmeters are not readily available. At frequencies up to 10,000 cps, thermocouple voltmeters can be used, but at higher frequencies, errors are introduced in this type due to skin effect in the multiplier. These voltmeters are more sensitive than dynamometer and iron-vane instruments but have the disadvantage that an overload greater than 50 percent may burn out the heater in a second or two. Rectifier type voltmeters can be used up to 20,000 cps, but accuracy is then sacrificed since these instruments have frequency, wave form, and temperature errors. At still higher frequencies, vacuum-tube voltmeters have to be used to minimize the frequency error.

- 2.31 Electrodynamic Voltmeters**—In electrodynamic voltmeters the deflection is the result of the reaction between one or more movable coils and the field produced by one or more fixed coils, the coils being connected in series and to the voltage to be

measured. The deflection of the movable system is a measure of the current in the circuit of the instrument and therefore of the voltage impressed at the terminals.

An important feature of electrodynamic voltmeters is that they can be calibrated with direct current, the average of a direct and a reverse reading being taken as the correct value. For commercial frequencies they are practically independent of frequency changes.

In most instruments of this type, a single coil moves within two parallel fixed coils. The deflection is a function of the square of the current in the coils and of the angle between the planes of the fixed and moving coils.

The "Thomson inclined-coil" voltmeter is of this class, except that the plane of the fixed coils makes an angle of about 45 degrees with the shaft of the moving coil for the purpose of extending the scale.

- 2.32 Soft-Iron-Vane Voltmeters**—This type utilizes the reaction between a temporarily magnetized piece or pieces of soft iron and the magnetizing field. In the "Thomson inclined-coil" instrument of this type the plane of the energizing coils makes an angle with the shaft, which carries a member comprising one or more approximately rectangular pieces of very thin, soft iron. These pieces of iron are attached to the shaft at an angle so that rotation is produced by the tendency of the iron to become parallel to the field established by the coils.

In "repulsion" instruments of this type, the reaction which produces the deflection may take place between two pieces of soft iron subjected to the same magnetic field. In the "book" or radial-vane type of instrument, one rectangular vane is attached to the instrument shaft. The other rectangular vane is attached to the field-coil frame and is stationary. When current is established in the field coil, both iron vanes are inductively magnetized in the same polarity, and their like poles therefore repel. These instruments have a substantially uniform scale. In the "concentric-vane" type the effect of increased vane separation as the pointer moves up-scale is obtained by tapering the vanes, so that there is less exposure of one to the other as the deflection increases. The concentric-vane construction requires more operating power than the radial-vane type and produces a less-uniform scale distribution. However it offers the advantage of scale-distribution control through special shaping of the vanes.

- 2.33 Damping of A-C Voltmeters**—In some instruments, air damping is provided by means of a light aluminum vane attached to the movable system and moving in a stationary enclosing chamber. In others, magnetic damping is effected by the motion of an aluminum plate between the poles of a permanent magnet.

- 2.34 Frequency Compensated Voltmeters**—This type has part of the series resistor shunted by a suitable capacitor to extend the frequency range over which the effect of inductive reactance appreciably changes the magnitude of the current through the instrument coil.

- 2.35 Thermocouple Voltmeters**—This type employs a fine heater wire in series with a resistor. A permanent-magnet moving-coil type of millivoltmeter is used to indicate the electromotive force produced in the thermocouple attached to the heater wire. The scale of a thermocouple instrument closely approximates a square-law scale since the power in the heater is proportional to the square of the current.

- 2.36 Rectifier Voltmeters**—Instruments of this type usually employ copper-oxide rectifiers. Usually four copper-oxide disks are connected in a circuit with a permanent-magnet moving-coil type milliammeter. Full-wave rectification of the alternating current is thus secured. Suitable series resistances are provided to give the desired ranges. The deflections are proportional to the average value of the current in the indicating instrument, but the scale is calibrated in rms values. Errors will result if the wave shape departs appreciably from a sine curve.

In making core loss measurements on transformers performance data on a sine-wave basis is standard. It is not always feasible to obtain a sine-wave voltage for these measurements and therefore two voltmeters, an average reading and an rms voltmeter, are used in determining the hysteresis and eddy-current losses. The hysteresis loss, which is the larger component depends upon the average voltage; the eddy-current loss depends upon the rms value of voltage. The usual procedure in core loss measurements is to set the value of any test voltage of the proper frequency by means of the average voltmeter of the rectifier type and note the corresponding watts and rms voltage.

- 2.37 Vacuum-Tube Voltmeters**—There is a great variety of vacuum-tube voltmeters available and care should be exercised in choosing one to assure that it is the type desired for the particular measurement being made.

The popularity of vacuum-tube voltmeters is chiefly due to their high input-impedance and wide frequency range. Most vacuum-tube voltmeters are calibrated in terms of the rms value of an applied sine wave voltage. However, since the instrument actually responds to the peak, peak-to-peak, or average value of the voltage wave, or some combination thereof, the indications of a vacuum-tube voltmeter on other than sine waves should be used with caution.

- 2.40 Measurement of High Voltages**—Theoretically any high voltage can be measured with a voltmeter having sufficient non-inductive resistance in series with it. Practically, this method is applicable up to only a few thousand volts because of the relatively large power consumption in the resistance and the necessity for insulating a cumbersome resistor. Also the method is dangerous with ungrounded systems. In alternating-current circuits, any considerable

amount of inductance and capacitance in the resistance must be avoided. The measurement of alternating voltages of more than 300 volts should preferably be made with a voltmeter and a calibrated instrument potential transformer.

When using a potential transformer with a voltmeter for measuring voltage, the true ratio should be known and this ratio when multiplied by the true volts corresponding to the indication of the voltmeter, gives the voltage being measured. The actual ratio may differ from the nominal ratio by as much as 0.5 to 1 percent; hence it should be known and not merely assumed to be the same as the nameplate value. For further discussion of potential transformers see INSTRUMENT TRANSFORMERS in this code.

High voltages are also measured with electrostatic voltmeters. These instruments are quite satisfactory for the measurement of high alternating voltages, but since the force developed between the plates is proportional to the square of the voltage low-torque difficulties are encountered at low voltages. They are provided with scales which make them direct reading and at low frequencies the power consumption is negligible. When used on direct current the electrostatic voltmeter becomes a zero-current device except for the initial charging current. Its use is, therefore, indicated in the measurement of high-voltage, low-current rectifier power supplies.

- 2.50 Range and Accuracy—See paragraph 1.40 and 1.41.
- 2.60 Procedure—See paragraph 1.51.
- 2.70 Precautions in Taking Readings—See paragraph 1.60.
- 2.80 Corrections—See paragraph 1.70.
- 2.90 Calibration of Voltmeters—Portable direct-current indicating voltmeters are calibrated (a) by comparison with a carefully calibrated laboratory standard voltmeter or (b) by direct comparison against a standard cell by means of a potentiometer and volt box. In either case, both are connected to a source of steady voltage which can be adjusted conveniently to any value by means of a rheostat or otherwise, and the readings of the standard are determined corresponding to various indications of the voltmeter being checked. A higher accuracy is obtained if the indication being checked is a graduation rather than an interpolated setting. Comparison at the major scale points is sufficient unless the subdivisions are obviously non-uniform.

Dynamometer types of alternating-current voltmeters with negligible inductance can be checked with direct current against a direct-current standard voltmeter or by direct comparison with a standard cell using a potentiometer and volt box. Direct and

reversed readings must be taken at each point. The true voltage as shown by the standard, is noted for a given indication of the instrument being checked with each direction of current through the instrument and the average is taken as the true value corresponding to the indication.

Soft-iron-vane instruments can be checked with direct current with only fair accuracy. With each direction of current the desired indication must be reached by carefully increasing from a lower value and again by decreasing from a higher value, care being taken to avoid overshooting in each case. Four values are thereby obtained which must be averaged.

If suitable facilities for a direct-current check are not available or the highest accuracy is desired, the calibration should be made with alternating current against a standard voltmeter of a type that can be calibrated on direct current. A standard so used is referred to as a "transfer instrument".

Thermocouple voltmeters can be calibrated with direct current taking direct and reversed readings, but calibration on 60 cps is preferred and is generally more accurate. Rectifier and vacuum-tube voltmeters should be calibrated with alternating voltages against secondary standards; the calibration of vacuum-tube voltmeters should be at sufficiently frequent intervals to compensate for changes in tube characteristics; intervals of 100 hours of use are suggested.

CURRENT MEASUREMENTS

- 3.10 Description—Current measurements in connection with this Code shall be made in general, with portable indicating ammeters. The principle of all ammeters is essentially the same as that of the electrodynamic, soft-iron-vane and thermocouple voltmeters described under VOLTAGE MEASUREMENTS. As stated under GENERAL in this Code the range of measurement of current is almost unlimited through the judicious use of auxiliary devices such as shunts for direct current and current transformers for alternating current.
- 3.20 Direct-Current Ammeters—Direct-current ammeters are usually low-range voltmeters connected across a resistor of low resistance (shunt) which is connected in series with the circuit in which the current is to be measured. The deflections will be proportional to the potential drop across the shunt and, therefore, to the current through it. This potential drop is kept small so that the energy loss in the shunt will not be large. Hence the instrument is essentially a millivoltmeter but the scale is usually graduated to read directly in amperes.
- 3.21 Portable Ammeters—Portable ammeters having ranges up to 25 amperes are usually "self-contained", that is, the shunt is within the instrument case. For ranges greater than 25 amperes the shunt is usually

separate from the instrument proper but connected to it by detachable leads.

- 3.22 Ammeter Shunts**—An ammeter shunt is constructed to have a resistance as nearly constant as possible, under all conditions. The resistance metal has a low temperature coefficient of resistance and the temperature is kept low either by connecting several strips in parallel and making the current density low, or if the current density must be high, using short lengths of the resistance metal with heavy copper terminals designed to dissipate the heat by conduction and radiation.

Furthermore, the resistance metal should have a low thermal emf against copper for two reasons: first, if one end of the shunt becomes hotter than the other because of poor contact at one current connection or to a poor connection in the cable or bus structure near that end of the shunt, a thermal emf will be produced in addition to the potential drop across the shunt; second, when current passes through the junction of two dissimilar metals which have a thermal emf with respect to each other, a Peltier effect results, that is, heat is absorbed or produced. Hence, one junction tends to become cool and the other to become hot and the resultant difference in temperature will produce an emf.

The potential drop in the shunt at full-scale deflection is usually about 50 to 200 millivolts. Instruments used for high-accuracy measurements are designed to require 100 to 200 millivolts at full scale. The shunt is usually separate from the instrument for all ranges of current so that one millivoltmeter may be used with several shunts. Whenever the shunt is separate from the instrument, the leads form a part of the instrument circuit and should never be altered without recalibrating the instrument or taking care that the resistance of the leads is kept the same as originally. In order not to introduce high contact resistance care should be taken that the terminals of leads, instrument, and shunt are clean and that the connections are tight. Obviously, broken strands of wire in flexible leads (such breaks frequently occur near the terminals) will introduce an error through change of lead resistance.

Direct-current ammeters are adjusted by changing the resistance of the shunt, the resistance of the millivoltmeter circuit, or both. Formerly, each instrument and shunt were adjusted together but it is becoming customary to adjust all of the instruments of a given type to deflect full scale with the same potential drop in millivolts at the terminals. The shunts for these instruments are all similarly adjusted to give the same potential drop, thus making all shunts and instruments of a given type interchangeable. The shunts should be adjusted by varying the resistance between the potential taps and not by adjusting a resistance wire connected in series with the instrument leads.

In the application of shunts to the measurement of direct current the precautions for use, as outlined in paragraph 3.23, should be followed if accurate and reliable measurement is to be secured.

- 3.23 Measurement of Large Direct Currents**—Large direct currents are measured in the same manner as small currents, *i.e.*, with millivoltmeters connected to shunts—the shunts being correspondingly larger in physical dimensions and lower in resistance. Certain precautions should be observed, however, when using large shunts. Shunts of several thousand amperes in capacity should be designed with long, multiple-leaf copper blocks to insure that the current distribution will be uniform through the shunt and will be the same after installation as when it was calibrated. Every time a large shunt is connected to a multiple-leaf bus structure, the contact resistance distribution is changed and if the junction is close to the resistance strips, the current will not be distributed uniformly among them.

In installing large capacity shunts in a bus structure they should preferably be placed in a horizontal bus run with the leaves mounted in a vertical plane, the shunts being so located in the bus structure as not to be immediately adjacent to right-angle turns in the bus. In addition, they should not be mounted in immediate proximity of large switches that are likely to "run hot" or any other heat producing element that would raise the temperature of the shunt unevenly and they should never be mounted vertically as the upper terminal would be heated by rising air currents. This latter practice would result in a thermal gradient across the shunt. All shunt connection surfaces should be clean and the joints made tight.

- 3.24 Transducers for Measurement of Large Direct Currents**—Large direct currents can also be measured by means of transducers which have the characteristics of current transformers. Transducers are sometimes used when the usual method of employing shunts is not convenient because of the size of the shunts and the difficulty of dissipating the losses occurring in them. A measuring transducer consists of two iron cores, called transducer elements, each forming a closed magnetic circuit around the d-c conductor. Each core has an a-c winding and the two windings are connected in series in such a manner that a current through them will in one of the coils assist the conductor field while in the other coil it will oppose it. The windings are energized with an alternating voltage and the current which flows is measured, preferably with a rectifier type ammeter. The rectified mean value of the alternating current is proportional to the direct current in the conductor. The a-c circuit is sufficiently sensitive to reflect closely the oscillations and variations in the direct current. Measuring transducers have a limiting error of \pm two percent or less, but in the smaller

direct-current ratings using a single turn primary, higher accuracy may require special core material.

- 3.30 Alternating-Current Ammeters**—Alternating-current ammeters for engineering measurements are usually of either the electrodynamic type or the soft-iron-vane type. The principle employed in each type is the same as that in the corresponding type of voltmeter, brief descriptions of which are given under VOLTAGE MEASUREMENTS. The construction may differ somewhat, however. In some modern dynamometer instruments over 0.5 or 0.75 ampere range, the fixed coils carry the total current to be measured while the movable coil is connected across a shunt which is in series with the fixed coils. Soft-iron-vane ammeters differ from voltmeters of the same type only in the size of wire and number of turns used. The same types of damping are employed in both.

Modern moving-iron ammeters can be used at any frequency up to 500 cps with practically no error. This is due to the fact that a frequency error is not caused by the inductive-reactance changes but only by the change in eddy-current losses. In frequency-compensated ammeters, these losses are reduced to a minimum by the use of high-resistivity material for the field coil form and low-hysteresis material in the magnetic circuit. As a result, errors in ammeters are reduced to low values over the frequency range of 60 to 3000 cps.

Thermocouple ammeters when properly designed to avoid skin-effect errors, may be used, practically without error, at all frequencies up to several megacycles.

Rectifier ammeters use a four-element copper-oxide rectifier in connection with a d-c milliammeter, the rectifier elements being so disposed that both half waves of current pass through the instrument. Rectifier ammeters are usually made with current ranges of a few milliamperes down to a range of 100 microamperes; they have a frequency error of about 0.5 percent per thousand cps up to about 20,000 cps, the reading decreasing as the frequency increases; a small amount of "reverse" current exists, but the scale is practically linear over a large part of the range; indications are proportional to the average value of the current, and if the scale is calibrated in rms values, errors occur with distorted wave shapes.

- 3.31 Measurement of Large Alternating Currents**—Alternating currents of high value (exceeding 100 amperes and sometimes less) are usually measured with current transformers and ammeters with a range of 5 or 10 amperes. See under INSTRUMENT TRANSFORMERS for a discussion of the use of this auxiliary apparatus.

- 3.40 Range and Accuracy**—See paragraph 1.40 and 1.41.

- 3.50 Procedure**—See paragraph 1.51.

- 3.60 Precautions in Taking Readings**—See paragraph 1.60. Special attention should be given in direct-current measurements to the connections between instrument and shunt, and between the shunt and the circuit in which it is connected. Contact surfaces should be kept clean, bright and tight. The connections of the shunt to the circuit is especially important in case of large shunts, as pointed out in the foregoing.

The measurement of large currents is particularly attended with risk of errors from stray magnetic fields, and the precautions previously given should be specially noted.

- 3.70 Corrections**—See paragraph 1.70. Error due to thermal emf at the potential terminals of ammeter shunts can be detected after breaking the main circuit. Observe the instrument reading and then break the main circuit. If the instrument shows a slight deflection, thermal emf is present. The readings should be corrected by algebraically subtracting the deflection observed immediately after opening the main circuit.

When using a current transformer in connection with an a-c ammeter the true ratio of the transformer should be known for several values of current. This ratio multiplied by the corrected instrument reading will be the value of current in the circuit, providing no other corrections are to be made. If the nominal or nameplate ratio is assumed to be correct, an error of from 0 to 1 percent may be introduced. See under INSTRUMENT TRANSFORMERS for further discussion.

- 3.80 Calibration of Ammeters**—A direct-current ammeter of ordinary range may be calibrated by connecting it in series with a suitable standard, such as a standard resistor across which a potentiometer is used to measure the potential drop. In some cases a laboratory standard millivoltmeter calibrated with standardized shunts is acceptable as a standard. The error is then noted at various points throughout the scale. In instruments of large range, the effect of heating should be determined by holding the current for some time at two-thirds to full-scale value, and then noting any change in the scale errors from the original value. See "Corrections".

When the rating of the instrument is beyond the facilities at hand, the resistance of the shunt between the potential taps can be accurately measured and the instrument itself (with its leads) checked separately as a millivoltmeter. For accurate work, the resistance of the shunt should be measured with a Kelvin bridge. Measurements should be made at several temperatures so that when the instrument is in use the true correction for any given load condition can be obtained by simply noting the corresponding shunt temperature measured with a

mercury-in-glass thermometer, or a thermocouple pyrometer, the bulb or junction of which is in contact with the resistance strips of the shunt. This temperature does not have to be measured accurately because the change in shunt resistance with change of temperature will be found to be relatively small.

Direct-current ammeters of large ranges consisting of a shunt resistor and a millivoltmeter have to be calibrated and checked separately, as indicated in the preceding paragraph. In measuring the resistance of large shunts for such a purpose, it is very important that the testing current be uniformly distributed throughout the shunt by having proper terminal connections to the test circuit. If the test circuit is connected only to one corner of the terminal blocks, for example, the current distribution will be far from uniform and the drop between the potential taps will not correspond to the true resistance.

Alternating-current ammeters are calibrated on the same principle as voltmeters, that is, by comparison with a standard ammeter which is of a type that can be calibrated with direct current. Such an instrument is called a "transfer instrument".

INSTRUMENT TRANSFORMERS

4.10 Function of Instrument Transformers—Instrument transformers often are used for operating control apparatus and for other similar purposes as well as in connection with electric instruments, but the only application which will be considered here will be that of measurements. In this connection they are used for the purpose of (a) reducing the voltages and currents to values which can be measured conveniently—usually values which can be measured with instruments having ranges not exceeding 150 volts and 5 amperes respectively, and (b) insulating the measuring instruments from the high potential which may exist on the circuit under test.

4.11 Distinctive Features—The principle of instrument transformers is similar to that of power transformers but, because of their special application, they differ from the latter in many particulars.

Current transformers consist of two windings particularly well insulated from one another and from the iron core upon which they are placed. The primary consists of a few turns, or even of only one turn in the form of a section of bus bar and is connected in series with the circuit under test. The secondary current corresponding to a given primary current is only slightly affected by the number of instruments connected in the secondary circuit (provided their total burden does not exceed the rating of the transformer); the characteristic is substantially constant current with variable voltage of a low value. Current transformers to be used in power lines are designed with a high short-time overload capacity in order that they shall not be-

come a hazard by rupturing when overloaded. Also, they are designed to have a low magnetizing current when operating at or below their rated burdens.¹

Current transformers to be used in power lines are designed with a high overcurrent capacity in order that they shall not become a hazard by failing thermally and/or mechanically.

Also, they are designed to operate at comparatively low flux densities and therefore low magnetizing current when operating at or below their rated burdens.

4.12 Types of Current Transformers—Portable current transformers are made in four types.

(a) With the primary winding divided into sections which can be connected in series or in parallel to change the ratio of transformation. The secondary winding is provided with a tap which is connected to a third secondary terminal for further change in the ratio of transformation.

(b) With no permanent primary winding, a conductor being threaded through the center of the iron core one or more times to form the primary circuit. The secondary circuit is permanently wound on the core. This is commonly called the "through" type.

(c) With no permanent primary winding and with a core which is split, hinged and provided with a clamp so that it can be slipped over the line conductor and clamped in position. This is commonly called the "split-core" type.

(d) Bushing type current transformers are mounted around the oil end of transformer or breaker bushings in generators. They are usually used for relaying but in many cases can be made accurate enough for metering. This type of current transformer consists of a cylindrical ring core, built up of thin iron laminations about which is wound insulated copper and/or aluminum wire to form the secondary winding. The transformer is installed in the housing of the bushing, with the high-tension conductor through the bushing, forming the one-turn primary winding of the current transformer.

4.13 Potential Transformers — Potential (voltage) transformers are quite similar in general design and in appearance to power transformers of small capacity, but they may have a higher magnetizing current because efficiency is of little or no importance. Both windings are of relatively small wire because only very small power capacity is required. The primary is connected directly to the line (often through protecting fuses) and the secondary to the instrument.

4.14 Polarity—When instrument transformers are used

with instruments or relays which operate only according to the magnitude of the current or voltage, the phase position is of no consequence and the connections to the secondary terminals may be interchanged without changing the indication of the instrument or the performance of relays. When instrument transformers are also used with wattmeters and certain other instruments the operation depends on the interactions of two currents, hence for the correct operation of such devices the currents must be in correct relative phase, and it becomes necessary to know the relative directions of the currents in primary and secondary windings of the instrument transformers. This is indicated by marking one primary and one secondary terminal with a distinctive polarity marker so that when the current direction is toward the transformer in the marked primary lead, it is away from the transformer in the marked secondary lead.

- 4.15 Rating**—Instrument transformers are rated according to the nominal ratio of primary to secondary current or voltage. They are also rated for (1) a definite burden¹ for which the transformer is compensated, or (2) the burden which the transformer will carry without causing errors greater than a specified amount. In the case of current transformers, the rated primary current and the maximum voltage of the circuit to which a transformer may be safely connected are also indicated. Similarly potential transformers are rated for a maximum safe primary voltage.

¹The burden of an instrument transformer is that property of the circuit connected to its secondary which determines the flow of true and reactive power from the transformer. It is expressed either as total ohms impedance, together with the effective resistance and reactance components of the impedance, or as the total volt-amperes and power factor of the secondary devices and leads. The values expressing the burden shall apply to the condition of rated secondary current or voltage of the instrument transformer and a stated frequency, both of which must also be included with the burden expression. The impedance expression is more applicable to current transformers, the volt-ampere, power factor expression to potential (voltage) transformers.

- 4.16 Advantages and Disadvantages in Using Instrument Transformers**—The particular advantages gained by using instrument transformers are:
- (a) Safety, because they permit the measuring instruments to be electrically insulated from the equipment under test.
 - (b) They permit the instruments to be located at any convenient place, not necessarily adjacent to the equipment under test.
 - (c) They make the wiring of the instruments much easier because of the small current and low voltage values.
 - (d) One set of instruments may be used with several transformers of suitable ratios for all measurements.

The only disadvantage in using instrument transformers is that in accurate measurements corrections must be determined and applied to the instrument

indications to take care of the variation of the actual ratio from the nominal ratio and also the variation of the phase angle from the ideal relation of 180 degrees displacement.

- 4.20 Range and Accuracy**—Current and potential transformers are available in standard makes for practically any desired range up to about 75,000 amperes and about 230,000 volts, respectively. Higher ranges may be obtained, but such transformers would be special.

In general, for particularly accurate measurements the secondary current of a current transformer should be between 25 and 100 percent of its rated current. Potential transformers are not, in general, required to operate at voltages far from their nominal ratings and their constants do not change materially with variations of the order of 10 percent from the rated voltage.

In certain cases, it is entirely possible that an error of the order of two percent may be introduced into the measurements by failure to make the necessary corrections for deviation from the nominal ratio of transformation and for phase-angle displacement. The magnitude of such corrections depends upon the burden (number and kind of instruments connected to the transformer), the secondary current (in the case of current transformers) and, in the case of power measurements, the power factor of the circuit being measured. Especially when measuring power at low power factor, correction for phase-angle displacement must be made because of the possible excessive error. See paragraph 5.85 under POWER MEASUREMENT, for discussion of phase-angle correction.

- 4.30 Grounding of Instrument Transformers** — In using instrument transformers, care should be taken to ground the frame or case and one side of the secondary circuit of each transformer in order to remove the danger to the observer and to the instruments should the insulation between primary and secondary break down. In grounding the secondary circuits of transformers connected to a poly-phase circuit, care must be taken not to ground at more than one point if the secondaries are interconnected; otherwise, a short circuit between phases will result. Figures 4.30-1 and 4.30-2 show the proper grounding connections for three-phase circuits.

- 4.40 Precautions in the Use of Instrument Transformers** — In using current transformers, care should be taken never to open the secondary circuit while current is in the primary winding because of the dangerously high voltage which may be developed and the excessive temperature rise which may ultimately take place due to high losses in the transformer. Also, opening the secondary circuit may leave the core of the transformer magnetized, resulting in a change in the ratio and phase-angle characteristics. When it is necessary to open the

secondary circuit, in order to change instruments for example, the secondary winding should be short-circuited, preferably at the transformer terminals.

If the secondary circuit is accidentally opened, possible magnetization of the core should be removed by either of the following two methods:

- (a) Short circuit the secondary through a 30-ohm resistor of sufficient current capacity and gradually increase the primary alternating current to full rated value after which it is gradually reduced to zero.
- (b) With the primary open, gradually increase the alternating current through the secondary to 5 amperes after which reduce it gradually to zero.

In the case of voltage transformers care should be taken to avoid short-circuiting the secondary. In other words, the circuit should be treated as any electric circuit of ordinary voltage. This circuit may, of course, be opened whenever desired.

The secondary circuits of instrument transformers should not be overloaded by placing too large burdens in them (that is, too many instruments, meters, relays, etc.) because of the resulting increase in the ratio and phase-angle errors.

Portable current transformers of the split-core type should be used with caution, particularly in power or energy measurements, because of the large ratio and phase-angle errors due to the high reluctance in the magnetic circuit and the possibility of change in this reluctance between the time of calibration and the time of use due to disturbing the joint in the magnetic circuit. In portable current transformers of the cable or "through" type where the primary conductor is passed through a hole in the core, each time the conductor passes through the hole it counts as one turn and the position of the conductor, or conductors in the hole, or the size and distribution of the loop between turns does not materially affect the ratio and phase angle. However,

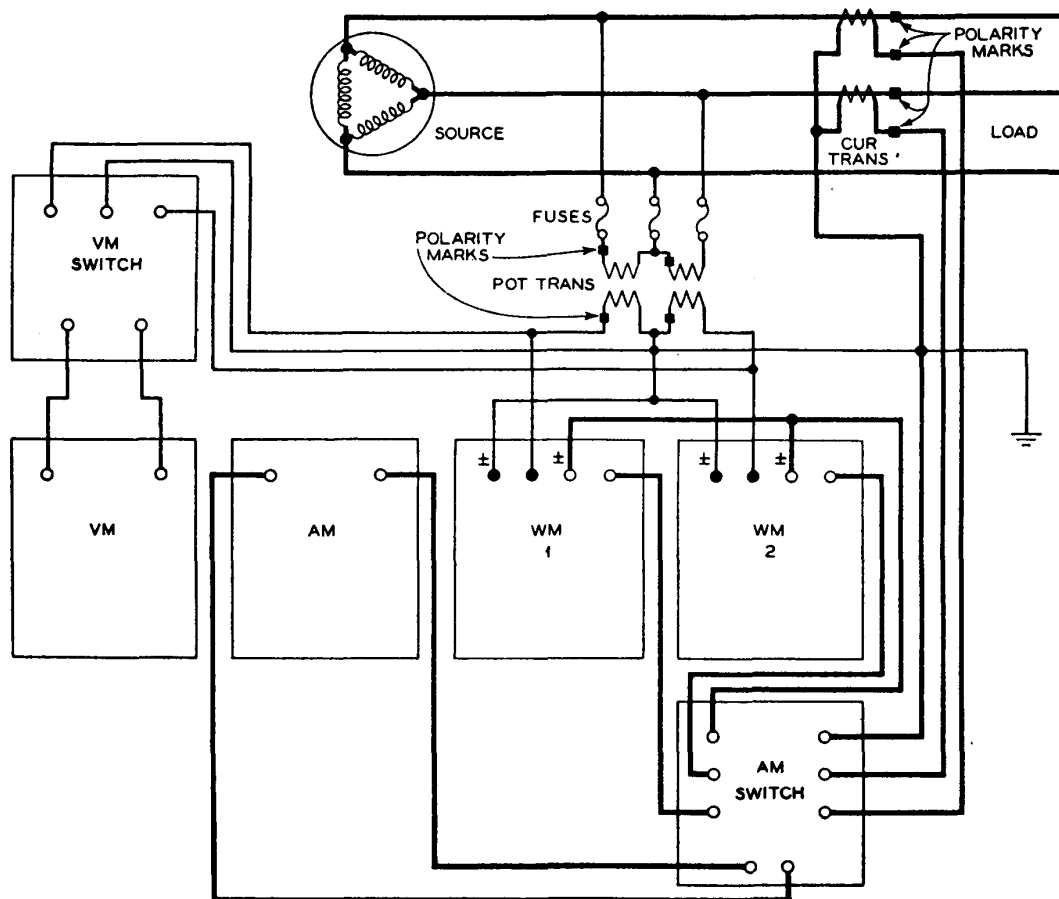


Fig. 4.30-1 Connections for the Measurement of Output of Alternating-Current, 3-phase, 3-wire Machine

a small error of the order of 0.1 percent in ratio or 5 minutes in phase angle may be the result and where this is significant the position of the conductors in the test should correspond with that used in the calibration.

4.50 Corrections — In an ideal current transformer having a core of infinite permeability, zero core loss, and no leakage flux, the secondary current would be exactly in opposition to the primary current and the ratio of transformation would equal the ratio of turns. Actually none of these conditions exist because of the current required to magnetize the core, the current required to supply the losses in the transformer, and other factors which depend upon the burden.

In some classes of engineering measurements these errors may be neglected entirely, but in accurate measurements of voltage, current, power, and energy, the true ratio should always be known. In addition the phase angle should be known in power and energy measurements. The corrections to be applied are discussed in detail under POWER MEASUREMENTS in this Code. In voltage

transformers, the primary voltage is substantially constant in most engineering measurements so that these errors need to be determined only for a small range of voltage. Modern voltage transformers show negligible variations of ratio and phase angle with deviations from rated voltage. The ratio is usually from 0.1 to 0.3 percent below nominal value for a small burden (one voltmeter) while the phase angle is practically negligible being slightly leading. But with the current transformer, measurements are made over a wide range of currents and, therefore, the errors should be determined under similar conditions. The error in percent of nominal ratio (or the ratio correction factor) and the phase-angle deviation for any particular reading are determined from the calibration curves for the transformer. Typical ratio and phase-angle curves are shown in figure 4.50-1.

4.60 Calibration—Instruments and their associated instrument transformers may be calibrated as units but, in general, this procedure is not as satisfactory as the separate calibration of the instruments and the transformers, particularly where the voltage of the

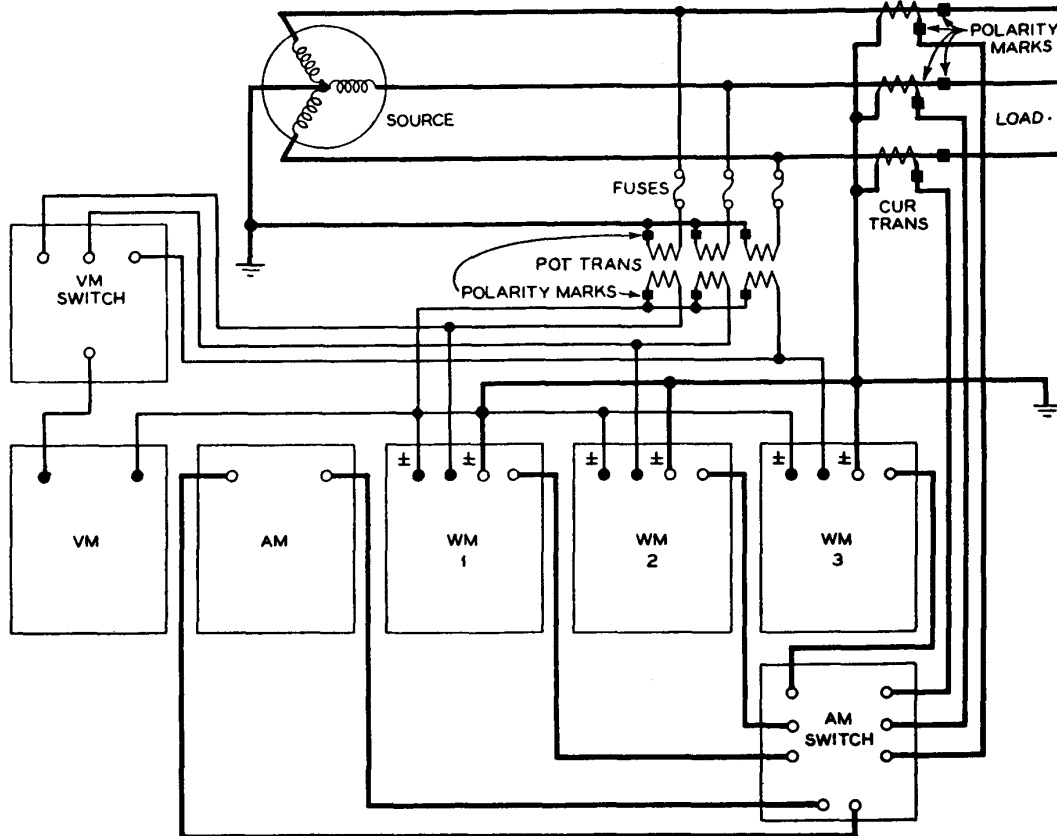


Fig. 430-2 Connections for Measurement of Output of 3-phase, 4-wire Machine

ASA STANDARD BURDENS, 60 CYCLES
 80.1 = 0.1 OHMS, 90% PF, 2.5 VA, AT 5 AMPERES
 80.5 = 0.5 OHMS, 90% PF, 12.5 VA, AT 5 AMPERES
 82 = 2.0 OHMS, 50% PF, 50.0 VA, AT 5 AMPERES

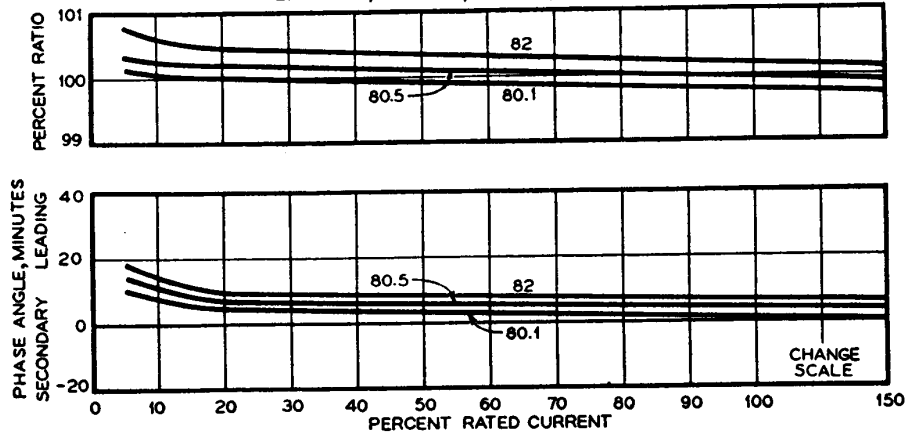


Fig. 4.50-1 Typical Ratio and Phase-Angle Curves for a Current Transformer

circuit exceeds a few hundred volts and the current exceeds 100 or 200 amperes. This is particularly true where power or energy measurements are involved because of the difficulty of measuring directly and with accuracy, power or energy involving high values of voltage or current. In the separate calibration of transformers, the ratio and phase-angle errors are determined by opposition methods which do not involve the measurement of voltages or currents but only the determination of the ratio of two quantities, such as resistances, readings of an ordinary indicating instrument, etc., depending upon the particular method employed. It is thus more precise and usually much more convenient to calibrate the instruments separately and measure the errors in the transformers directly. This separate test has the further advantage that any damage to one or more of the instruments or a change of their constants, does not require a repetition of the test of the entire measuring apparatus. Good instrument transformers may be depended upon to maintain their constants unchanged for a much longer period of time and service than instruments or meters.

The calibration necessary is the determination of the ratio of transformation and phase-angle deviation for various values of secondary burden and at various percentages of rated primary current. However, if the transformer is to be used with a particular instrument or set of instruments, the calibration should be made with the corresponding value of secondary burden.

As mentioned in paragraph 4.20, current measurements cover a wide range of values and a current transformer should, therefore, be calibrated over a correspondingly wide range of currents. However, in voltage measurements the variation of voltage is usually very small and in such cases, the calibra-

tion may resolve itself into a single-point determination.

A number of methods are available for determining the ratio and phase-angle errors of instrument transformers. Descriptions will be found in the textbooks on electrical measurements, and in the limited bibliography listed below. In general, the calibration of instrument transformers can be properly done only in a well-equipped electrical laboratory having facilities for that particular class of work.

4.61 Bibliography Covering Instrument Transformers

- (1) Silsbee, F. B.: Methods for testing current transformers. American Institute of Electrical Engineers Transactions, 43, 282, (1924).
- (2) Werres, C. O.: Hand, A. R.: La Pierre, C. W.: Shunt method of testing current transformers. General Electric Review, 41, 370, (1938).
- (3) Fortescue, C. Le G.: Calibration of current transformers by means of mutual inductances. American Institute of Electrical Engineers Transactions, 34, 1599, (1915).
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- (6) Arnold, A. H. M.: Current transformer testing. Institution of Electrical Engineers Journal (British), 74, 424, (1934).

- (7) Bousman, H. W.: Ten Broeck, R. L.: A capacitance bridge for determining the ratio and phase angle of potential transformers. American Institute of Electrical Engineers Transactions, 62, 541 (1943).
- (8) Brooks, H. B.: Testing potential transformers. Bulletin of the National Bureau of Standards, 10, 419, (1914).
- (9) Leeds and Northrup Co.: Potential transformer testing set. Bulletin No. 716.
- (10) Hague, B. Pitman (London) 1936: Instrument transformers—their theory, characteristics and testing. (A very complete discussion of all phases of the subject with many references.)
- (11) Park, J. H.: Accuracy of high-range current transformers. National Bureau of Standards Journal of Research, 14, 367, (1935) (R. P. 775).
- (12) Park, J. H.: Effective of wave form upon the performance of current transformers. National Bureau of Standards Journal of Research, 19, 517, (1937).

POWER MEASUREMENTS

5.10 Description—The power being expended in a circuit is the algebraic average of the products of simultaneous instantaneous values of the current and the voltage. With direct current, the power (in watts) is equal to the product of the voltage (in volts) and the current (in amperes). In symbols, $P = EI$. With alternating current the power (in watts) is equal to the product of the effective value of the voltage (in volts), the effective value of the current (in amperes) and the power factor (which for sine waves is the cosine of the phase angle between current and voltage) or

$$P = EI \cos \theta$$

where P = power in watts

E = voltage in volts

I = current in amperes

$\cos \theta$ = power factor

5.20 Direct-Current Power—Direct-current power is practically always best determined from the product of current and voltage measured simultaneously. Wattmeters (described below) may be used to measure the power directly thus requiring only one instrument. However, the use of a wattmeter for direct-current power measurements is somewhat inconvenient in that it is necessary to take the mean of two measurements, the current and voltage connections being reversed for the second. This precaution is necessary because unshielded wattmeters are particularly subject to error from local magnetic fields, and even shielded wattmeters sometimes develop magnetic poles in the shield. It is, therefore, usual to measure direct-current power by simultaneous measurement of current and voltage.

5.30 Alternating-Current Power—Alternating-current

power is most directly and accurately measured with wattmeters, instruments which indicate directly the algebraic average of the products of the instantaneous values of current and voltage. In other words, they indicate directly the true power irrespective of the wave shape or the character of the load.

5.31 Wattmeters—The essential elements of a wattmeter are:

- (a) A current circuit
- (b) A voltage circuit
- (c) A mechanism for indicating the instantaneous product of current and voltage and averaging the result over short intervals of time.

Practically all portable wattmeters used in accurate engineering measurements are of the electrodynamic type.

5.32 Electrodynamic Wattmeters—The electrodynamic type of instrument employs a current element and a potential element. The current or series element consists of two fixed coils wound with heavy wire or strip, connected in series with each other and with the main circuit. The potential element is a moving coil mounted on a shaft supported between jewel bearings and placed between the two fixed coils. This coil consists of a large number of turns of fine wire as in voltmeters; it is connected in series with a relatively large amount of non-inductive resistance, across the main circuit. The controlling force is provided by one or more spiral springs. The kinds of damping employed are similar to those used in alternating-current voltmeters.

5.33 Polyphase Wattmeters—The polyphase wattmeter is essentially a combination of two single-phase instruments, there being two sets of fixed and moving coils but with the moving coils mounted on a common shaft. A polyphase wattmeter is connected to the circuit just as two separate single-phase instruments would be connected.

5.34 Induction Type Wattmeters—The induction type wattmeter is merely a miniature induction motor in which rotation of the moving element is opposed by a spiral spring, causing an attached pointer to deflect an amount which is proportional to the torque developed in the moving element.

It is obvious that instruments of the induction type are limited to the frequency for which they are designed.

5.35 Laboratory Standard Wattmeters—Semi-portable wattmeters designed primarily for use in the laboratory as secondary standards of reference employ the same electrodynamic principle previously described. They are constructed with special care to eliminate sources of error, such as eddy currents in supporting parts and in the current windings. They are larger and, in general, more carefully constructed and adjusted than instruments of lesser accuracy.

5.40 Range and Accuracy—See paragraph 1.40 and 1.41.

5.50 Procedure—Care should be taken to connect a wattmeter into the main circuit so that the moving-coil end of the potential circuit and the current coil are on the same side of the circuit being measured. When used with instrument transformers the moving-coil end of the potential circuit should be con-

nected to the grounded terminal of the potential transformer. Otherwise there may be sufficient electrostatic attraction between the two windings to produce an error; or, if the potential is sufficiently high, the insulation between the windings may be broken down. In polyphase instruments used in polyphase systems without instrument transformers there is little choice of connections on the above basis.

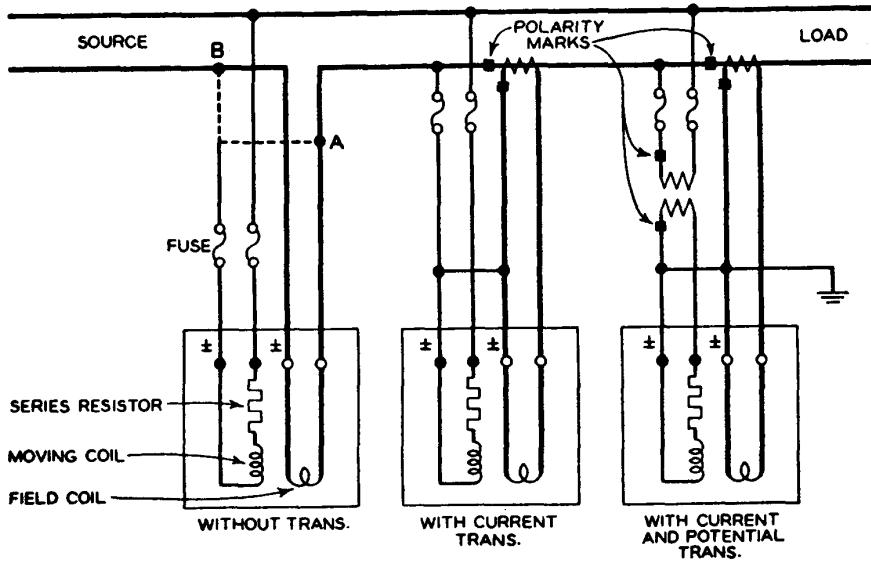


Fig. 5.51-1 Power Measurements in Single-Phase Circuits with Wattmeter

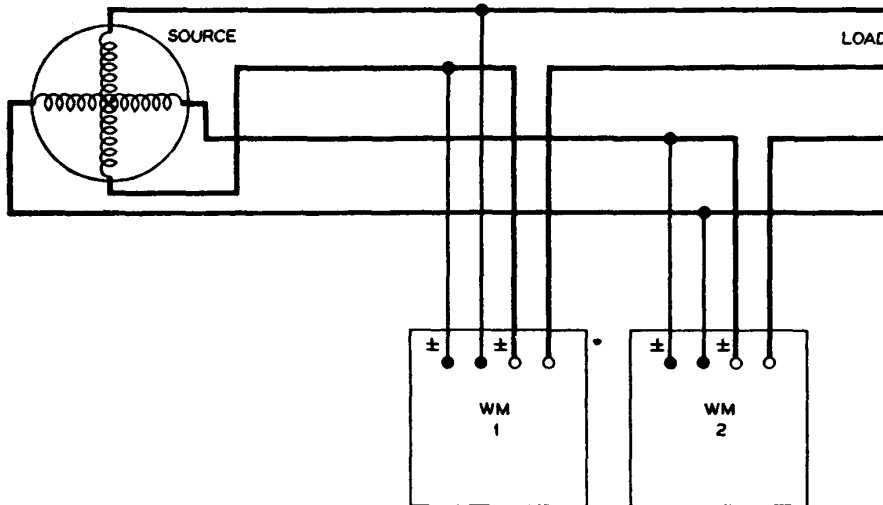


Fig. 5.52-1 Power in 2-phase, 4-wire Circuit (Not Interconnected)

5.51 Measurement of Power in a Single-Phase Circuit—One wattmeter connected as shown in figure 5.51-1, A, will measure the power dissipated in the load if correction is made for the power loss, $\frac{E^2}{R}$, in the potential circuit of the wattmeter. If the connection of the potential circuit is made at the line side, B, instead of the load side, A, correction for the power loss, I^2R , in the current circuit must be made.

5.52 Two-phase, Four-wire Circuit (Not Interconnected)—Two wattmeters are connected as shown in figure 5.52-1, the conditions being equivalent to two single-phase circuits. The total power is ob-

viously the arithmetical sum of the readings of the two instruments.

5.53 Three-wire Circuit—Two wattmeters should be connected as shown in figure 5.53-1, the total power being the algebraic sum of the two readings.

This connection is correct for single, two, or three phase, under all conditions of load, balance and power factor. Since one meter may be negative on low power factor, facilities for reversing polarity should be provided when required.

5.54 Two-phase, Four-wire, Interconnected Circuit—Three wattmeters should be used, connected as in figure 5.54-1 the total power being the algebraic

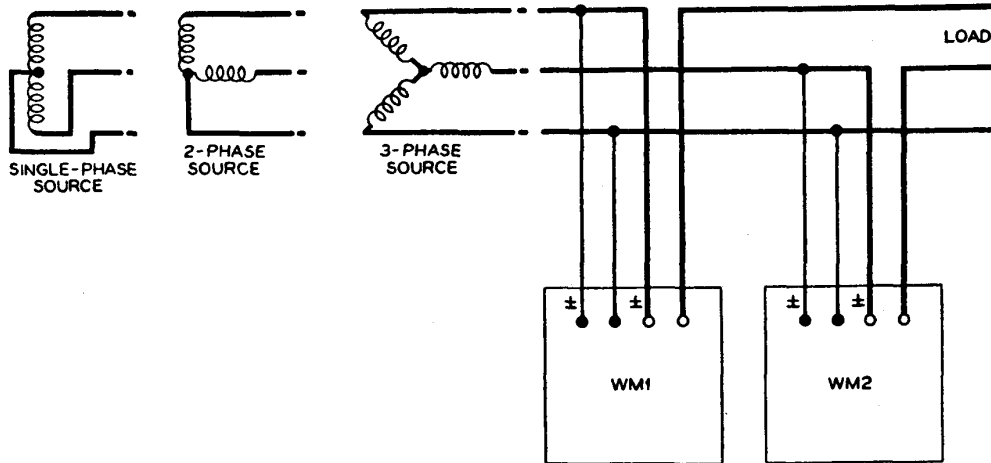


Fig. 5.53-1 Power in Single-phase, 2-phase, or 3-phase, 3-wire Circuit

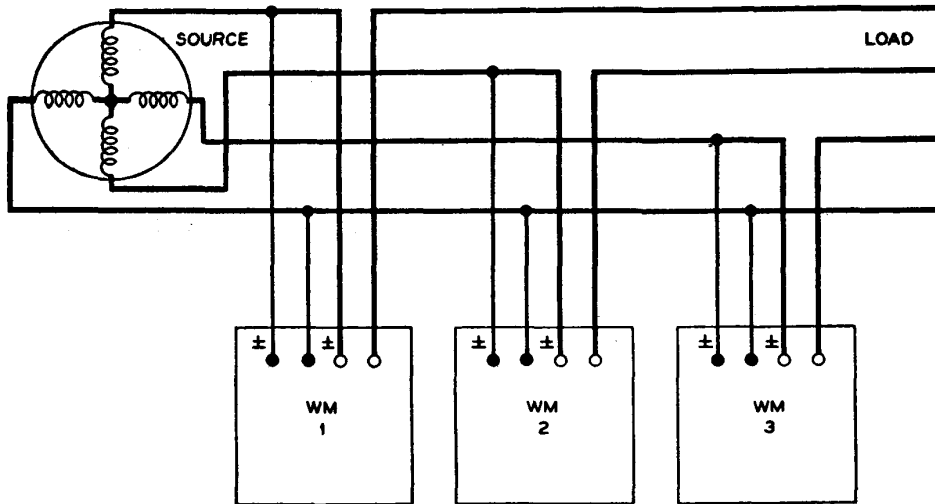


Fig. 5.54-1 Power in 2-phase, 4-wire Interconnected Circuit

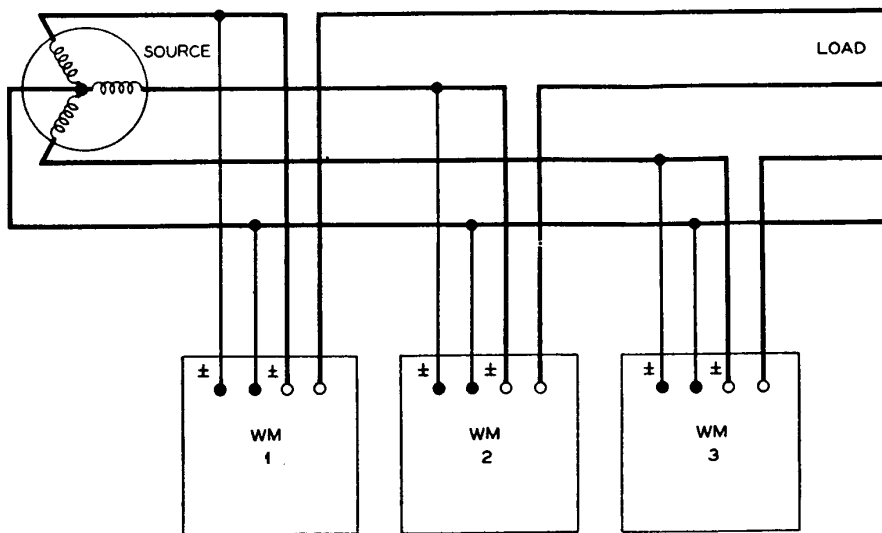


Fig. 5.55-1 Power in 3-phase, 4-wire Circuit, Using Three Wattmeters

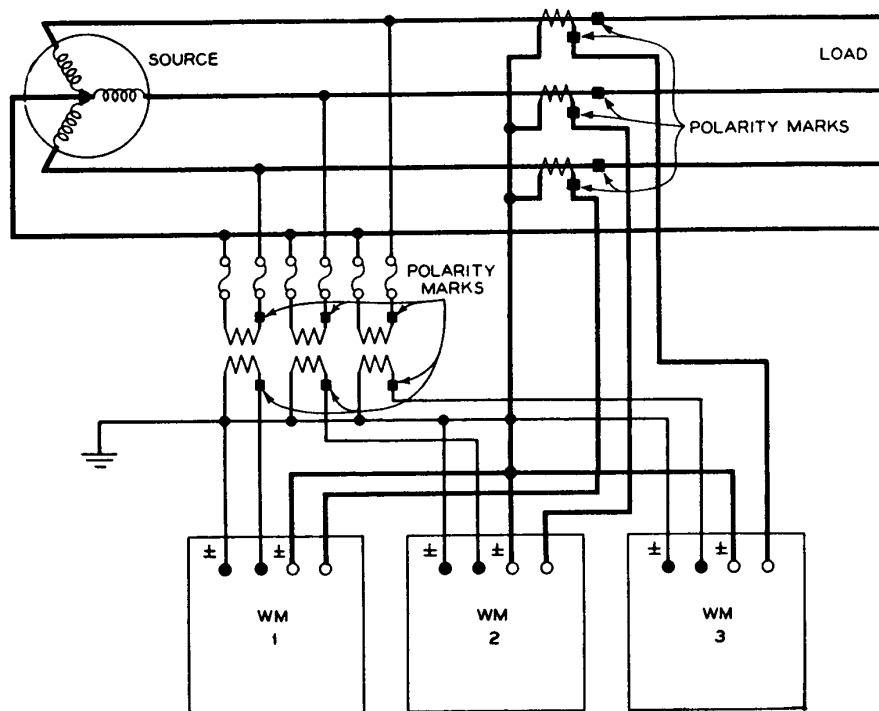


Fig. 5.55-2 Connections with Both Potential and Current Transformers in 3-phase, 4-wire circuit, Using Three Wattmeters

sum of the three readings. This connection is correct under all conditions of load, balance and power factor. It should be noted that the voltage impressed on WM3 is 1.414 times that impressed on WM1 and WM2. Two wattmeters, one in each phase, will give the true power only when the load on all four legs is balanced.

- 5.55 Three-phase, Four-wire Circuits**—Three wattmeters are used as shown in figure 5.55-1. The total power is the algebraic sum of the three readings. This method is correct under all conditions of load, balance, and power factor. A three-phase, "star" system with a grounded neutral is virtually a four-wire system and the power should be measured with three wattmeters. Obviously, if the load is balanced, one wattmeter can be used, the total power being the indication of the wattmeter multiplied by three. The current coil should be connected in series with one conductor or phase wire and the potential coil between that conductor and the neutral when one wattmeter is used. When used with instrument transformers connections are as shown in figure 5.55-2.
- 5.56 "N"-wire Circuit**—In any system whatsoever, of "N" wires, the true power may be measured by connecting a wattmeter in each line but one ($n-1$ wattmeters), the current coil being in series with the line and the potential coil connected between that line and the line which contains no current coil. The total power for any load condition is the algebraic sum of the readings of all the wattmeters so connected. Providing a grounded neutral connection to load or source should be held equivalent to adding another wire.
- 5.57 Artificial Neutrals**—Where the load is balanced in all respects, the power in three-phase, three-wire circuits is sometimes measured with one wattmeter connected in one phase and to an artificial neutral obtained by means of (1) a star or Y-box composed of two additional resistors equal in value to the wattmeter's voltage circuit and multiplying reading by 3; or (2) a center-tapped autotransformer across two phases with instrument connected from center tap to the third phase, whose current is used. The reading is multiplied by 2. These methods are not recommended for accurate measurements.
- 5.58 Use of Polyphase Wattmeters**—The two elements of a polyphase wattmeter may be used instead of two single-phase wattmeters on three-phase circuits, particularly where the load is very unsteady or where a continuous record is being obtained with recording instruments. The two-instrument method is, however, the preferred one for most reliable results because the various transformer and instrument errors can be more accurately corrected for, especially at low power factors, despite the fact that the two-instrument method requires the calibration and reading of two instruments instead of one.
- 5.60 Measurement of Large Powers**—Measuring large power presents no unusual difficulties. Current and potential transformers of suitable ranges are employed with a wattmeter which usually has 5 and 10 ampere current ranges and 75 and 150 volt potential ranges. The instrument transformers are usually at some distance from the wattmeter, and, if proper ground connections have been made, no special difficulty due to stray magnetic or electrostatic fields will be found. (See paragraph 4.30 and 5.50).
- 5.70 Precautions in Taking Readings**—Spring changes due to temperature variation may be considerable; hence it is generally advisable, where the duration of the test is sufficient, to pre-heat the wattmeters for 30 minutes after which they should be momentarily de-energized to adjust the zero indication. See also paragraph 1.60 n.
- 5.80 Temperature Errors**—Change in temperature alters the resistance of the moving coil. The effect of this change in resistance may be reduced to a negligible value by the instrument designer, when the voltage of the circuit is sufficiently high, by the use of series resistance wire having a low temperature coefficient. With some of the higher grade wattmeters, that is, secondary standards, the makers furnish a temperature coefficient which should be applied in accurate measurements, particularly where the voltage is low and the series resistance in the potential circuit is relatively small.
- 5.81 Inductance Errors**—The inductance errors in wattmeters may require consideration when measurements are made at low power factors. While the elementary theory of the electrodynamic type of wattmeter assumes that the voltage circuit is non-inductive, this is not strictly true in the actual instrument because of the self-inductance of the moving coil. Ordinarily, however, the non-inductive series resistance is sufficiently large to make the effect of this inductance negligible at ordinary frequencies and high power factors. The phase angle of the voltage circuit in good wattmeters, for frequencies of 25 to 60 cps and voltage ranges of 100 to 150 volts, will be from 2 to 10 minutes. Assuming 6 minutes as an average value, the resulting error from this cause alone will be 0.3 percent when a load of power factor 0.50 is measured. At power factor 0.90 the error is less than 0.1 percent. In using a wattmeter in connection with instrument transformers, it is convenient to combine the phase angle of the wattmeter with those of the current transformer and the voltage transformer (See paragraph 5.85).
- 5.82 Stray-Magnetic-Field Errors** — The stray-field error in unshielded, nonstatic electrodynamic watt-

meters placed in an alternating magnetic field of 5 oersteds may be anything from zero to 25 percent, depending upon the direction of the field and the coil deflection. A shield, properly made and placed, is extremely efficient, reducing the effect of a field as strong as 20 oersteds to practically zero without introducing eddy current or other errors. The latest types of wattmeters are provided with such shields in the form of a well, built up of rings of laminated steel, in which wattmeter elements are mounted.

A stray field is indicated when, with the potential coils alone connected to the main circuit, a deflection is obtained. If the stray field is constant in direction and magnitude its effect may be eliminated from a measurement by rotating the instrument until this deflection becomes zero and noting the direction of the pointer (with respect to some point external to the instrument). Then, with the current circuit connected, the instrument is rotated until the deflected pointer is in the same position as before; the stray field then has no effect on the moving coil and there will be no error. The effect of weak fields may be eliminated most easily by providing reversing switches for both current and voltage circuits and taking the average of the readings with direct and reversed connection. Note that current reversing switches must be of the shorting type, while voltage reversing switches must be of the momentary open type.

Wattmeters of the Kelvin-balance type, in which the coils are astatically arranged, are practically immune from errors due to stray fields, except in an intense field, which is not uniform throughout the space occupied by the moving system. Such a condition may arise, for example, when the wattmeter is close to a conductor carrying a very large current.

5.83 Electrostatic-Field Errors—As in all moving-coil instruments, an error may be caused by electrostatic attraction between the movable coil of the wattmeter and an adjacent body at a different potential. This adjacent body is usually within the instrument itself. A charge may be induced on the glass¹ over the scale or on the metal cover (where the case is non-metallic) by accidental rubbing and this will attract the pointer causing a false deflection. Such a condition is readily removed by breathing on the glass or case.

An error from this cause is frequently encountered when the wattmeter is being used with its potential and current circuits connected to separate sources between which there is a difference of potential, thus causing an electrostatic force between the fixed and movable coils. The remedy in this case is, of course, to so connect the two coils in the circuit that they are practically at the same potential. If this is not readily obvious by inspection, the similarly marked terminal of each circuit can be connected

together. To insure that the coils are at the same potential and to avoid accident in case the circuits are accidentally connected at some other point, this connection at the wattmeter may be first made through a voltmeter which should always indicate zero. If the instrument reads in the wrong direction, the connections to the current coil should be reversed.

If the wattmeter is being used with current and potential transformers, electrostatic errors may be quite troublesome, unless the circuits are connected together at one terminal. (See paragraph 4.30).

¹Some instruments have plastic windows instead of glass. In these, the error due to accidental rubbing is apt to be appreciable. Care should be taken to remove the charge by breathing on the plastic window.

5.84 Errors Due to Instrument Losses—As mentioned in paragraph 5.51, when a simple (uncompensated) wattmeter is connected in a circuit, the power which it measures will include that expended either in the current coil or the voltage circuit, depending upon whether the current through the potential coil flows through the current coil or whether the power loss in the current coil is included in the measurement. Figure 5.51-1 Connection A shows the instrument so connected that the power loss in the potential circuit, E^2/R , is included in the measurement. If the potential circuit connection is moved from *A* to *B*, the power loss in the current circuit, I^2R , is included in the measurement. It must be remembered that the losses of other voltage circuits such as those of voltmeters, recording wattmeters, and watt-hour meters, may be included when using the connection of figure 5.51-1. Likewise, the current coil losses in ammeters, wattmeters, etc., may be included when the potential circuit connection is moved from *A* to *B*. The error so caused is ordinarily negligible, but may become important when measuring small powers. The correction is readily calculated if the resistances of the instrument circuits are known. The connection of the potential circuit to *A* is generally preferable since the correction is constant for a given voltage while the correction for the connection of the potential circuit to *B* varies as the square of the load current.

Some wattmeters are provided with a compensating field winding which automatically corrects for the loss in its voltage circuit. Such wattmeters¹ are very convenient when many measurements of small amounts of power have to be made, but they require somewhat more circumspection on the part of the user as to correctness of connections and, of course, the compensation is for the wattmeter voltage circuit only.

¹Compensated wattmeters should not be used in conjunction with either current or potential transformers.

A circuit to correct ammeter and wattmeter readings for current drawn by voltmeter and watt-

meter potential coils is described and illustrated in AIEE Miscellaneous Paper 49-275 dated September 1949. This method eliminates the calculations necessary to correct for instrument losses where the voltage drop in the ammeter and the current coil of the wattmeter is negligible.

5.95 Phase-Angle Errors—There are three phase-angle errors to be considered in making accurate power measurements when using both current and potential transformers. They are: (1) the phase-angle error in the potential circuit of the wattmeter; (2) the phase-angle error of the current transformer; and (3) the phase-angle error of the potential transformer. They are usually designated by the Greek symbols, α , β , and γ , respectively. The effect of these phase-angle errors is to make the angle between the current in the fixed coils and the current in the moving coils of the wattmeter larger or smaller than that between the current and the potential of the circuit being measured; the error thereby produced depends on the power factor of the main circuit.

The phase-angle error in the potential circuit of the wattmeter, α , can be determined from the values of L and R which are often found either in the instrument cover or listed as burden data in manufacturer's catalogues on instrument transformers. From the value of L , the reactance of the potential coil circuit becomes, $X = 2\pi fL$, where f is the frequency at which the power measurement is made. R is the resistance of the wattmeter potential coil. The phase-angle error is then

$$\alpha = \tan^{-1} \frac{X}{R}$$

The sign of α is to be considered positive if X is capacitive and negative if X is inductive.

The phase-angle error of the wattmeter should correctly also include the minor effects of eddy currents, mutual inductance, and any peculiarities of internal circuit or construction, and the total may be considered as the instrument phase-angle error. At 60 cps these additional effects are usually small so that the instrument phase-angle error is considered as that of its potential circuit. But for some types of compensated wattmeters at 60 cps and for all instruments at higher frequencies more exact information should be requested from the manufacturer or be obtained by test.

The phase-angle error of the current transformer, β , is obtained from the test certificate specifying the value of the phase-angle error for the burden connected to the transformer secondary. Where the actual burden differs from that which was used in the certification test, the phase angle may be estimated from characteristic curves of phase angles at specific burdens. The sign of β is to be considered positive when the secondary current leads the primary current.

The phase-angle error of the potential transformer, γ , is determined in the same manner as the current transformer. The sign of γ is to be considered positive when the secondary voltage leads the primary voltage.

It will be observed from the above that all leading angles are considered positive which facilitates committing them to memory. Since signs have been assigned to these phase angles, it is convenient to associate a sign with the power-factor angle of the metered load for the purpose of adding or subtracting the angles in determining their effect. Lagging power-factor angles are to be considered positive and leading power-factor angles negative.

In order to correct wattmeter readings for phase-angle errors, it is necessary to determine the phase-angle correction factor (PACF). This factor is expressed mathematically as

$$\text{PACF} = \frac{\cos \theta}{\cos \theta_s}$$

where $\cos \theta$ = true power factor and $\cos \theta_s$ = apparent power factor.

The true power-factor angle, θ , between the primary current and primary voltage is obtained by algebraically adding the phase-angle error of the wattmeter potential coil, the phase-angle error of the current transformer, and the phase-angle error of the potential transformer, to the apparent power factor angle, θ_s . Then

$$\theta = \theta_s - \alpha + \beta - \gamma$$

$$\text{PF} = \cos \theta = \cos (\theta_s - \alpha + \beta - \gamma)$$

$$\text{PACF} = \frac{\cos (\theta_s - \alpha + \beta - \gamma)}{\cos \theta_s}$$

The value obtained for the phase-angle correction factor from this last formula along with the ratio correction factor for the current and potential transformers, and the wattmeter scale correction, are to be used in determining the true power.

Example of Wattmeter Reading Corrected for Phase-Angle Errors of Wattmeters and Ratio and Phase-Angle Errors of Instrument Transformers.

Data:

Lagging current $f = 60$ cycles

C.T. Ratio = 39.64:1

P.T. Ratio = 19.94:1

Voltage = (19.94) (104.4) = 2082

Current = (39.64) (2.5) = 99.1

Volt Amperes = (99.1) (2082) = 206,330

Wattmeter reading = 53

Apparent watts = (53) (39.64) (19.94) = 41,893

Apparent pf = $\cos \theta_s = \frac{41,893}{206,330} = 0.20304$

$\theta_s = 78^\circ 17'$

Note: θ_s = apparent angle of lag includes the

phase angle of the wattmeter, α ; the phase angle of the current transformer, β ; and the phase angle of the potential transformer, γ .

The values of L and R for the wattmeter as obtained from the instrument cover are 0.0034 henry and 5000 ohms respectively. Therefore:

$$\alpha = -\tan^{-1} \frac{2\pi fL}{R} = -\tan^{-1} \frac{2\pi \times 60 \times 0.0034}{5000} = -1'$$

$$\beta = +55'$$

$$\gamma = +38'$$

$$\begin{aligned} \text{Then } \theta, \text{ true lag angle} &= \theta_s - \alpha + \beta - \gamma \\ &= 78^\circ 17' - (-1') + \\ &\quad (+55') - (+38') \\ &= 78^\circ 35' \end{aligned}$$

$$\text{True pf} = \cos \theta = 0.1979$$

$$\text{PACF} = \frac{\cos \theta}{\cos \theta_s} = \frac{0.1979}{0.20304} = 0.9747$$

$$\text{True Power} = 41,893 \times 0.9747 = 40,833 \text{ watts}$$

The true power may also be determined using Tables I and II which give the phase-angle correction factors when the combined phase angle ($-\alpha + \beta - \gamma$) and the apparent power factor are known. In this example, the combined phase-angle error ($-\alpha + \beta - \gamma$) = $+18'$. Interpolating between phase angles $15'$ and $20'$ we get for a combined phase angle of $18'$, the phase-angle correction factor 0.9743 at an apparent power factor of 0.200. Again, interpolating between $15'$ and $20'$ we get for a combined phase angle of $18'$, the phase-angle correction factor 0.9797 at an apparent power factor of 0.250 (This part of the interpolation should always be done before interpolating between values of power factor). Interpolating between these two values of phase-angle correction factor (0.9743 and 0.9797) we get at an apparent power factor of 0.203 a phase-angle correction factor of 0.9746.

Using this value of phase-angle correction factor we get

$$\text{True Power} = 41,893 \times 0.9746 = 40,829 \text{ watts}$$

The discrepancy between this value obtained through the use of the tables and that obtained from the calculation of the phase-angle correction factor, is attributable to the unavoidable error in interpolating but this difference is much less than the errors of observation.

When a balanced three-phase load is measured with a two-element polyphase wattmeter, and the ratio and phase-angle characteristics of the transformers used with the two elements are identical, the phase-angle correction factor can be computed on a single-phase basis. The power factor of the load can be conveniently found from the ratio of the readings of the wattmeter, first with one element alone, then with the other element alone. From this ratio, $\cos \theta_s$, the apparent power factor of the load

as determined from the secondary currents and voltages, may be obtained from the formulas given in paragraph 8.31. The true power factor of the load, $\cos \theta$, is then $\cos (\theta_s - \alpha + \beta - \gamma)$ as in the single-phase case.

5.90 Calibration of Wattmeters—Wattmeters of the electrodynamic type are calibrated with direct current, taking the average of direct and reversed readings. It is customary to make such tests at a fixed voltage, usually 100 or 200 volts, and to vary the current to give the required watts. The voltage is held constant at some convenient value by means of one standard (standard voltmeter or potentiometer) and the current is read on another standard (standard ammeter or potentiometer with standard resistor). Of course, one potentiometer may perform both functions by utilizing throw-over switches. It is convenient to obtain the voltage and the current from separate sources, because then the process of adjusting one circuit will not affect the other. Also in the case of instruments of large capacity, this scheme economizes energy as only 3 or 4 volts are necessary for the current circuit.

Portable wattmeters can also be calibrated with alternating current by comparison with carefully calibrated laboratory standard wattmeters. In this method the current coils of the standard and portable wattmeter are connected in series and the potential coils are connected in parallel. The current for the current coils can be supplied by the secondary of a loading transformer whose primary voltage can be conveniently varied by means of an autotransformer.

The potential for the potential coils can also be supplied by another variable autotransformer. Care should be exercised to make sure that the wave shape of the current and potential supply is sinusoidal and approximately in phase. (See paragraph 6.81).

Polyphase wattmeters are customarily checked in the same manner by connecting the current coils in series and the potential coils in parallel which makes the instrument single phase. Care should be taken, however, that the two elements are closely equal in accuracy and particularly that there is no inductive interference between the two elements due to the magnetic field from one affecting the other. Equality of the elements can be tested by connecting the potential coils in parallel and the current coils in series, but with the current in one coil reversed. Then if the elements are equal, the indication will be zero. This test for equality, however, is limited in its scope, for it checks the equality only for the relative coil positions corresponding to zero deflection. By shifting the spring abutments so as to bring the reading (with no current flowing) to 10, 20, 30 divisions, the equality may be checked for these positions. If the spring abutments cannot

TABLE I
CORRECTION FACTORS $\left(\frac{\cos \theta}{\cos \theta_2}\right)$ FOR PHASE ANGLES

For Lagging Current When $(-\alpha + \beta - \gamma)$ Is Positive
For Leading Current When $(-\alpha + \beta - \gamma)$ Is Negative

Phase-angle ($-\alpha + \beta - \gamma$)	Apparent Power Factor (Cos θ_2) †													
	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95	0.99	1.00
5'	0.9855	0.9904	0.9929	0.9944	0.9954	0.9967	0.9975	0.9981	0.9985	0.9989	0.9993	0.9995	0.9998	1.0000
10'	0.9711	0.9808	0.9857	0.9887	0.9907	0.9933	0.9950	0.9961	0.9970	0.9978	0.9986	0.9990	0.9996	1.0000
15'	0.9566	0.9712	0.9786	0.9831	0.9861	0.9900	0.9924	0.9942	0.9955	0.9967	0.9979	0.9986	0.9994	1.0000
20'	0.9421	0.9616	0.9715	0.9775	0.9815	0.9867	0.9899	0.9922	0.9940	0.9956	0.9972	0.9981	0.9992	1.0000
25'	0.9276	0.9520	0.9643	0.9718	0.9768	0.9833	0.9874	0.9903	0.9926	0.9945	0.9965	0.9976	0.9989	1.0000
30'	0.9131	0.9424	0.9572	0.9662	0.9722	0.9800	0.9848	0.9883	0.9911	0.9934	0.9957	0.9971	0.9987	1.0000
40'	0.8842	0.9232	0.9429	0.9549	0.9629	0.9733	0.9798	0.9844	0.9881	0.9912	0.9943	0.9961	0.9983	0.9999
50'	0.8552	0.9040	0.9286	0.9436	0.9536	0.9666	0.9747	0.9805	0.9851	0.9890	0.9929	0.9951	0.9978	0.9999
1° 0'	0.8262	0.8848	0.9143	0.9323	0.9444	0.9599	0.9696	0.9766	0.9820	0.9868	0.9914	0.9941	0.9974	0.9998
10'	0.7972	0.8656	0.9000	0.9209	0.9350	0.9531	0.9645	0.9726	0.9790	0.9845	0.9899	0.9931	0.9969	0.9998
20'	0.7682	0.8464	0.8857	0.9096	0.9257	0.9464	0.9594	0.9687	0.9760	0.9823	0.9885	0.9921	0.9964	0.9997
30'	0.7392	0.8271	0.8714	0.8983	0.9164	0.9397	0.9543	0.9648	0.9730	0.9800	0.9870	0.9911	0.9959	0.9997
40'	0.7102	0.8079	0.8571	0.8869	0.9071	0.9329	0.9492	0.9608	0.9699	0.9778	0.9855	0.9900	0.9954	0.9996
50'	0.6812	0.7886	0.8428	0.8756	0.8978	0.9262	0.9441	0.9568	0.9668	0.9755	0.9840	0.9890	0.9949	0.9995
2° 0'	0.6521	0.7694	0.8284	0.8642	0.8884	0.9194	0.9389	0.9529	0.9638	0.9732	0.9825	0.9879	0.9944	0.9994
10'	0.6231	0.7501	0.8141	0.8529	0.8791	0.9127	0.9338	0.9489	0.9607	0.9709	0.9810	0.9869	0.9939	0.9993
20'	0.5941	0.7308	0.7997	0.8415	0.8697	0.9059	0.9287	0.9449	0.9576	0.9686	0.9795	0.9858	0.9934	0.9992
30'	0.5650	0.7115	0.7854	0.8301	0.8603	0.8991	0.9235	0.9409	0.9545	0.9663	0.9779	0.9847	0.9928	0.9990
40'	0.5360	0.6923	0.7710	0.8187	0.8510	0.8923	0.9183	0.9369	0.9515	0.9640	0.9764	0.9836	0.9923	0.9989
50'	0.5069	0.6730	0.7566	0.8073	0.8416	0.8855	0.9132	0.9329	0.9483	0.9617	0.9748	0.9825	0.9917	0.9988
3° 0'	0.4779	0.6537	0.7422	0.7959	0.8322	0.8787	0.9080	0.9288	0.9452	0.9594	0.9733	0.9814	0.9912	0.9986
10'	0.4488	0.6344	0.7279	0.7845	0.8228	0.8719	0.9028	0.9248	0.9421	0.9570	0.9717	0.9803	0.9906	0.9985
20'	0.4198	0.6131	0.7135	0.7731	0.8134	0.8651	0.8976	0.9208	0.9390	0.9547	0.9701	0.9792	0.9900	0.9983
30'	0.3907	0.5957	0.6991	0.7617	0.8040	0.8583	0.8924	0.9167	0.9359	0.9523	0.9686	0.9781	0.9894	0.9981
40'	0.3616	0.5764	0.6847	0.7503	0.7946	0.8514	0.8872	0.9127	0.9327	0.9500	0.9670	0.9769	0.9888	0.9980
50'	0.3326	0.5571	0.6702	0.7388	0.7852	0.8446	0.8820	0.9086	0.9296	0.9476	0.9654	0.9758	0.9882	0.9978
4° 0'	0.3035	0.5378	0.6558	0.7274	0.7758	0.8377	0.8767	0.9046	0.9264	0.9452	0.9638	0.9746	0.9876	0.9976
10'	0.2744	0.5185	0.6414	0.7160	0.7663	0.8309	0.8715	0.9005	0.9232	0.9429	0.9622	0.9735	0.9870	0.9974
20'	0.2453	0.4991	0.6270	0.7045	0.7569	0.8240	0.8663	0.8964	0.9201	0.9405	0.9605	0.9723	0.9864	0.9971
30'	0.2163	0.4798	0.6125	0.6930	0.7474	0.8171	0.8610	0.8923	0.9169	0.9381	0.9589	0.9711	0.9857	0.9969
40'	0.1872	0.4604	0.5981	0.6816	0.7380	0.8103	0.8558	0.8882	0.9137	0.9357	0.9573	0.9699	0.9851	0.9967
50'	0.1581	0.4411	0.5837	0.6701	0.7285	0.8034	0.8505	0.8841	0.9105	0.9333	0.9556	0.9687	0.9844	0.9964
5° 0'	0.1290	0.4217	0.5692	0.6586	0.7191	0.7965	0.8452	0.8800	0.9073	0.9308	0.9540	0.9675	0.9838	0.9962
10'	0.0999	0.4024	0.5548	0.6472	0.7096	0.7896	0.8400	0.8759	0.9041	0.9284	0.9523	0.9663	0.9831	0.9959
20'	0.0708	0.3830	0.5403	0.6357	0.7001	0.7827	0.8347	0.8717	0.9008	0.9260	0.9507	0.9651	0.9824	0.9957

Interpolation for correction factors corresponding to values $(-\alpha + \beta - \gamma)$ lying between those given in the table, may be made without error. Interpolation for correction factors corresponding to values of $\cos \theta_2$ lying between those given in the table, may be made without exceeding an error of 0.0010 in the sections of the tables lying between the heavy black lines; outside of these sections, and in all cases where the adjacent values of $\cos \theta_2$ are separated by the heavy black lines the maximum error in interpolation will exceed 0.0010.

ACCORDING TO ASA STANDARDS:

α IS POSITIVE WHEN THE CURRENT IN THE WATTMETER POTENTIAL CIRCUIT LEADS THE VOLTAGE.

β IS POSITIVE WHEN THE SECONDARY CURRENT LEADS THE PRIMARY CURRENT.

γ IS POSITIVE WHEN THE SECONDARY VOLTAGE LEADS THE PRIMARY VOLTAGE.

† IN THE CASE OF POLYPHASE MEASUREMENTS, THE METER OR ELEMENT IN EACH PHASE MUST BE CORRECTED SEPARATELY, CONSIDERING θ AS THE ANGLE BETWEEN THE VOLTAGE AND CURRENT ON THE METER OR ELEMENT BEING CORRECTED (NOT THE ANGLE REPRESENTED BY THE POLYPHASE POWER FACTOR).

TABLE II
CORRECTION FACTORS $\left(\frac{\cos \theta}{\cos \theta_2}\right)$ FOR PHASE ANGLES

For Lagging Current When $(-\alpha + \beta - \gamma)$ Is Negative
For Leading Current When $(-\alpha + \beta - \gamma)$ Is Positive

Phase-angle ($-\alpha + \beta - \gamma$)	Apparent Power Factor ($\cos \theta_2$) †													
	0.10	0.15	0.20	0.25	0.30	0.40	0.50	0.60	0.70	0.80	0.90	0.95	0.99	1.00
5'	1.0145	1.0096	1.0071	1.0056	1.0046	1.0033	1.0025	1.0019	1.0015	1.0011	1.0007	1.0005	1.0002	1.0000
10'	1.0289	1.0192	1.0142	1.0113	1.0092	1.0067	1.0050	1.0039	1.0030	1.0022	1.0014	1.0010	1.0004	1.0000
15'	1.0434	1.0288	1.0214	1.0169	1.0139	1.0100	1.0075	1.0058	1.0044	1.0033	1.0021	1.0014	1.0006	1.0000
20'	1.0579	1.0383	1.0285	1.0225	1.0185	1.0133	1.0101	1.0077	1.0059	1.0043	1.0028	1.0019	1.0008	1.0000
25'	1.0723	1.0479	1.0356	1.0281	1.0231	1.0166	1.0126	1.0097	1.0074	1.0054	1.0035	1.0024	1.0010	1.0000
30'	1.0868	1.0575	1.0427	1.0338	1.0277	1.0200	1.0151	1.0116	1.0089	1.0065	1.0042	1.0028	1.0012	1.0000
40'	1.1157	1.0766	1.0569	1.0450	1.0369	1.0266	1.0201	1.0154	1.0118	1.0087	1.0056	1.0038	1.0016	0.9999
50'	1.1446	1.0958	1.0711	1.0562	1.0461	1.0332	1.0251	1.0193	1.0147	1.0108	1.0069	1.0047	1.0020	0.9999
1° 0'	1.1735	1.1149	1.0853	1.0674	1.0553	1.0398	1.0301	1.0231	1.0177	1.0129	1.0083	1.0056	1.0023	0.9998
10'	1.2024	1.1340	1.0995	1.0787	1.0645	1.0464	1.0351	1.0269	1.0206	1.0151	1.0097	1.0065	1.0027	0.9998
20'	1.2313	1.1531	1.1137	1.0898	1.0737	1.0530	1.0400	1.0308	1.0235	1.0172	1.0110	1.0074	1.0030	0.9997
30'	1.2601	1.1722	1.1279	1.1010	1.0829	1.0596	1.0450	1.0346	1.0264	1.0193	1.0123	1.0083	1.0034	0.9997
40'	1.2890	1.1913	1.1421	1.1122	1.0921	1.0662	1.0500	1.0384	1.0292	1.0214	1.0137	1.0091	1.0037	0.9996
50'	1.3178	1.2104	1.1562	1.1234	1.1012	1.0728	1.0549	1.0421	1.0321	1.0235	1.0150	1.0100	1.0040	0.9995
2° 0'	1.3466	1.2294	1.1704	1.1346	1.1104	1.0794	1.0598	1.0459	1.0350	1.0256	1.0163	1.0109	1.0044	0.9994
10'	1.3755	1.2485	1.1845	1.1457	1.1195	1.0859	1.0648	1.0497	1.0379	1.0276	1.0176	1.0117	1.0047	0.9993
20'	1.4043	1.2675	1.1986	1.1569	1.1286	1.0925	1.0697	1.0535	1.0407	1.0297	1.0189	1.0126	1.0050	0.9992
30'	1.4331	1.2866	1.2127	1.1680	1.1377	1.0990	1.0746	1.0572	1.0435	1.0318	1.0202	1.0134	1.0053	0.9990
40'	1.4618	1.3056	1.2268	1.1791	1.1469	1.1055	1.0795	1.0610	1.0464	1.0338	1.0215	1.0142	1.0055	0.9989
50'	1.4905	1.3246	1.2409	1.1902	1.1560	1.1120	1.0844	1.0647	1.0490	1.0359	1.0227	1.0150	1.0058	0.9988
3° 0'	1.5194	1.3436	1.2550	1.2013	1.1650	1.1185	1.0893	1.0684	1.0520	1.0379	1.0240	1.0158	1.0061	0.9986
10'	1.5481	1.3626	1.2691	1.2124	1.1741	1.1250	1.0942	1.0721	1.0548	1.0399	1.0252	1.0166	1.0063	0.9985
20'	1.5768	1.3816	1.2832	1.2235	1.1832	1.1315	1.0990	1.0758	1.0576	1.0419	1.0265	1.0174	1.0066	0.9983
30'	1.6056	1.4005	1.2972	1.2346	1.1923	1.1380	1.1039	1.0795	1.0604	1.0439	1.0277	1.0182	1.0068	0.9981
40'	1.6343	1.4195	1.3113	1.2456	1.2013	1.1445	1.1087	1.0832	1.0632	1.0459	1.0289	1.0190	1.0071	0.9980
50'	1.6630	1.4384	1.3253	1.2567	1.2103	1.1509	1.1136	1.0869	1.0660	1.0479	1.0301	1.0197	1.0073	0.9978
4° 0'	1.6916	1.4573	1.3393	1.2677	1.2194	1.1574	1.1184	1.0906	1.0687	1.0499	1.0313	1.0205	1.0075	0.9976
10'	1.7203	1.4763	1.3533	1.2788	1.2284	1.1638	1.1232	1.0942	1.0715	1.0519	1.0325	1.0212	1.0077	0.9974
20'	1.7489	1.4952	1.3673	1.2898	1.2374	1.1703	1.1280	1.0979	1.0742	1.0538	1.0337	1.0220	1.0079	0.9971
30'	1.7776	1.5141	1.3813	1.3008	1.2464	1.1767	1.1328	1.1015	1.0770	1.0558	1.0349	1.0227	1.0081	0.9969
40'	1.8062	1.5329	1.3953	1.3118	1.2554	1.1831	1.1376	1.1052	1.0797	1.0577	1.0361	1.0234	1.0083	0.9967
50'	1.8348	1.5518	1.4092	1.3228	1.2644	1.1895	1.1424	1.1088	1.0824	1.0596	1.0373	1.0241	1.0085	0.9964
5° 0'	1.8634	1.5707	1.4232	1.3337	1.2733	1.1959	1.1472	1.1124	1.0851	1.0616	1.0384	1.0248	1.0086	0.9962
10'	1.8920	1.5895	1.4371	1.3447	1.2823	1.2023	1.1519	1.1160	1.0878	1.0635	1.0396	1.0255	1.0088	0.9959
20'	1.9205	1.6083	1.4510	1.3557	1.2912	1.2086	1.1567	1.1196	1.0905	1.0654	1.0407	1.0262	1.0089	0.9957

Interpolation for correction factors corresponding to values $(-\alpha + \beta - \gamma)$ lying between those given in the table, may be made without error. Interpolation for correction factors corresponding to values of $\cos \theta_2$ lying between those given in the table, may be made without exceeding an error of 0.0010 in the sections of the tables lying between the heavy black lines; outside of these sections, and in all cases where the adjacent values of $\cos \theta_2$ are separated by the heavy black lines the maximum error in interpolation will exceed 0.0010.

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- β IS POSITIVE WHEN THE SECONDARY CURRENT LEADS THE PRIMARY CURRENT.
- γ IS POSITIVE WHEN THE SECONDARY VOLTAGE LEADS THE PRIMARY VOLTAGE.
- † IN THE CASE OF POLYPHASE MEASUREMENTS, THE METER OR ELEMENT IN EACH PHASE MUST BE CORRECTED SEPARATELY, CONSIDERING θ AS THE ANGLE BETWEEN THE VOLTAGE AND CURRENT ON THE METER OR ELEMENT BEING CORRECTED (NOT THE ANGLE REPRESENTED BY THE POLYPHASE POWER FACTOR).

be shifted enough to bring the coil successively into positions closely spaced (say every 10 divisions) over the whole range of deflections to be used, the equality over the part of the scale inaccessible by the preceding method should be checked by comparing the separate tests of the two elements. This may require the overloading of the current coil or the voltage coil or both, but modern wattmeters are usually designed with a rather liberal permissible overload beyond the rated values of current and voltage.

ENERGY MEASUREMENTS

- 6.10 Description**—While the principal measurements in tests of electric power equipment are usually made with indicating instruments, it is often desirable to check the energy consumption as computed from the power and time measurements by direct measurements with energy meters. It is probably true that if the quantities being measured are reasonably steady and constant, measurements with wattmeters and a stop watch will give more accurate and reliable results than an energy meter. On the other hand, there are conditions where wattmeters cannot be used with reliable results and an energy meter must be depended upon as the principal instrument, the average power being computed by dividing the total energy consumption by the elapsed time. For example, the output of a generator may have to be determined with a load of such a fluctuating character that it would not be practicable to take readings of a wattmeter sufficiently often to give an accurate result for average power or for total energy delivered. A similar condition would be encountered with a motor driving a machine having a rapidly changing load cycle. In case the test period is relatively short a portable watthour meter may be used.

A device which measures electrical energy is known as a watthour meter (sometimes called an *integrating wattmeter*). All watthour meters are practically small motors in which one revolution of the rotating element represents a certain amount of energy, the speed being proportional to the power. The revolving element operates a registering mechanism on which the energy consumption corresponding to the total number of revolutions is recorded. Meters for direct current are usually of the type which utilize the electrodynamic principle of direct-current motors, while those for alternating current utilize the principle of induction motors.

Watthour meters regularly used as working standards for testing purposes (called *test meters*, *rotating standards* and *standard watthour meters*) differ from those used for the commercial measurement of electrical energy in that they are designed with more attention to details which affect the accuracy, are more portable, are provided with several current and voltage ranges and are usually

equipped with a sweep pointer and a register which indicates revolutions and fractions of a revolution directly, thus permitting the accurate measurement of much smaller quantities of energy. The principle and general construction are, however, just the same in the two forms.

- 6.20 Types of Direct-Current Watthour Meters**—Direct-current energy is measured with two types of watthour meters: commutator meters and mercury-motor meters.

- 6.21 Commutator Type Meters**—The essential features are shown in figure 6.21-1. The rotating element consists of an armature *a*, a commutator *c*, and a light metal disc *d*, all mounted on a steel shaft which rotates in a jeweled bearing. The disc *d* rotates between the poles of two or more permanent magnets. The armature is connected to the external circuit by means of very light silver-tipped brushes. In series with the armature are a light-load compensation coil *s* and a resistance *r*. In some meters the resistor, *r*, is included in the compensating coil *s*. The field coils are indicated at *ff*.

The principle of operation of commutator type meters is as follows: Since there is no iron in the magnetic circuits of the driving motor, the torque is proportional to the product of line current and line voltage, *i.e.*, to the power. The eddy currents induced in the disk react with the permanent-magnet field, producing a counter torque which will always be proportional to the speed. Thus, theoretically, the speed will always be proportional to the power in the circuit. Each revolution represents a definite amount of energy, and by connecting the shaft to a suitable registering mechanism, the total energy consumed is automatically registered.

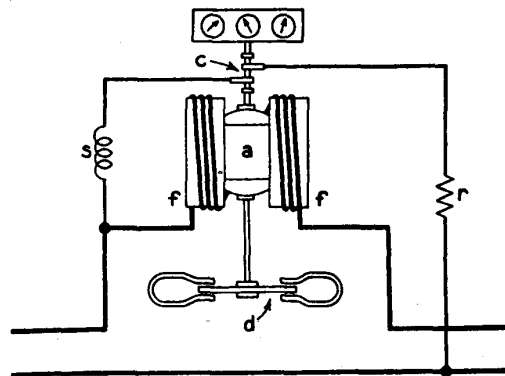


Fig. 6.21-1 Illustrating principle of commutator type watthour meters.

- 6.22 Compensation for Friction in Commutator Type Meters**—This is furnished by a compensating device which usually consists of a coil of about the same diameter as the field coils *ff*, connected in series with the armature and mounted so that the magnetic

field it produces is added to that of the main field coils. The amount of compensation produced can be adjusted for each meter individually by altering the position of the coil with respect to the field coils.

6.23 Compensation for Temperature in Commutator Type Meters—Temperature affects the performance of meters by (a) changing the resistance of the potential circuit; (b) changing the resistance of the drag disc; and (c) changing the strength of the permanent magnets. These changes produce a combined or resultant effect, which is compensated for, to a considerable extent, by using for a series resistance in the potential circuit, one or more materials so combined that the resultant or final temperature coefficient of resistance counteracts the other effects.

6.24 Mercury-Motor Meters—This type of meter has no lower bearing or commutator so that it has a possible advantage where there is excessive vibration or where the meter is subject to shock. Figure 6.24-1 shows diagrammatically the circuits and scheme of operation of such a meter. *D* is a slotted copper disk floating in mercury; *F* is a float which supports the shaft and eliminates a lower bearing; *H* is a laminated iron core and *C* is a chamber filled with mercury. The flux produced in the core *H*, by the shunt coil, traverses the disk at two points which are diametrically opposite. The line current passes from *L* to *L*₁, through the mercury and diametrically (due to the slots) through the disk. The reaction between this current and the flux of right angles to it develops a torque which is proportional to the product of the current and the voltage.

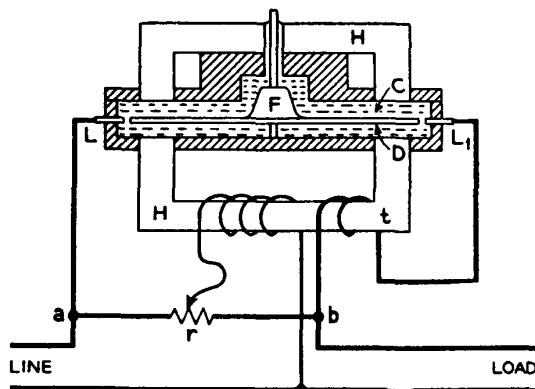


Fig. 6.24-1 Illustrating one method of compensation for mercury-motor meters.

6.25 Compensation for Friction in Mercury-Motor Meters—The friction due to the disk rotating in the mercury is compensated in two ways. One method is shown in figure 6.24-1. A high resistance, *r*, is connected in shunt with the armature *D*, and the potential circuit is completed by the sliding contact,

P. When the slider is at *b*, practically all of the voltage-circuit current will pass through *D* because of the resistance, *r*, thus adding to the torque. When the slider is at *a*, practically none of the potential-coil current will traverse the armature. In the second method, a circuit consisting of two wires of dissimilar metals which form a thermocouple, is connected in parallel with the mercury-chamber terminals, *L*, *L*₁. This couple is surrounded with a heating coil connected in series with the potential circuit. The emf produced by the thermocouple causes current to flow through the disk, thus producing the necessary additional torque to overcome the effect of friction at light load. The effect of the increased mercury friction at high speed is counteracted by a series turn *t*, on the core *H*. The drag or counter torque is obtained with a separate disk and permanent magnets (not shown).

6.30 Alternating-Current Watthour Meters—Alternating-current watthour meters are practically universally of the induction type. They operate on the principle of the rotating magnetic field of the induction motor. The essential features of the principal makes of watthour meters are shown in the diagrammatic sketch, figure 6.30-1. *P* is the potential coil, *S* is the series coil, and *C* is the compensating coil. A metallic disk is free to revolve between the poles. The alternating magnetic fluxes from these poles will establish currents in the disk about as indicated by the circular lines in the sketch at the right, which shows a portion of the disk and the relation of the poles to the disk when mounted. The potential winding *P* has many turns and is, therefore, highly inductive so that the flux emanating from the potential pole tip will lag almost 90 degrees behind the applied voltage.

On the other hand, the fluxes set up by the line current in coils *S* are in phase with that current. Since the emf generated in a conductor by a flux which cuts it is in time quadrature with the flux, it follows that at unity power factor load current, the eddy currents produced in the disk by the flux from *P* will be a maximum at almost the same instant that the flux from *S* is a maximum. And, contrariwise, the eddy currents set up in the disk by the fluxes from *S* (one-quarter period later) will be at a maximum at almost the same instant that the flux from *P* is a maximum. Thus a torque will be produced which is proportional to the instantaneous product of the eddy currents in the disk and the flux from the pole around which the current is flowing. This torque will be proportional to the power used in the load circuit providing the time-phase difference of the currents in coils *P* and *S* is exactly 90 degrees at unity power factor. The necessary retarding action or counter torque is obtained with permanent magnets acting on this same disk.

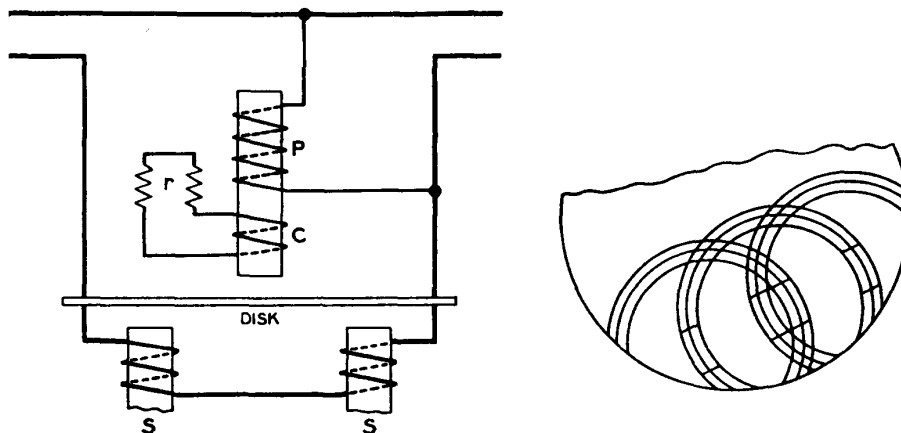


Fig. 6.30-1 Illustrating principle of induction type alternating-current watt-hour meters.

6.31 Compensation Coil for Induction Type Meters—

If the phase quadrature is not exact, the meter will obviously not register correctly under every condition. In consequence of the ohmic resistance of the potential circuit, the current is never exactly 90 degrees behind the impressed voltage. At any instant, the flux E_f (See figure 6.31-1) from the potential coil, instead of being in phase with the eddy currents, I_e , due to the line current, is slightly ahead, as indicated. The torque is, therefore, proportional to the product I_e and oa , instead of I_e and E_f . The meter will, therefore, run slow, but as a practical matter the error is so small at unity power factor that it is insignificant. The error rapidly becomes large, however, as the power factor decreases. As practically all alternating-current circuits have a power factor less than unity, a compensating coil (lag coil, is used to eliminate the error. This is the short-circuited coil C placed on the potential pole (figure 6.30-1) and in which a current is

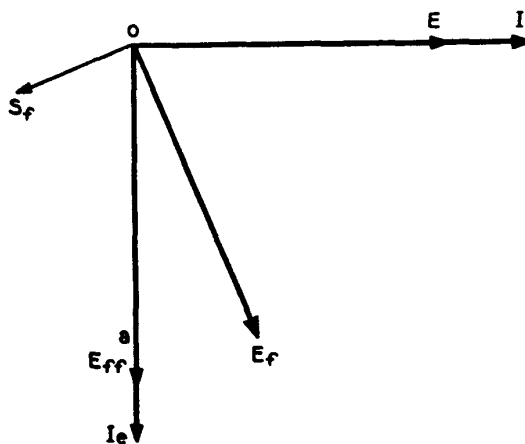


Fig. 6.31-1 Theory of lag adjustment, induction watt-hour meter.

induced a little more than 90 degrees behind the generating (potential) flux. Its flux S_f will be in phase with that (induced) current and, therefore, 90 degrees from E_f , with which it will combine. By adjusting the value of the resistance (lag adjustment) r , the resultant flux E_{ff} can be brought into exact phase with I_e under a set of specific conditions; residual errors at other power factors and loads will then be very small. It is evident that with lagging power factor in the circuit, a meter will be slow if "underlagged" and fast if "overlagged". Obviously, the opposite results will occur with a leading power factor.

6.32 Friction Compensation—The friction in an induction type meter is much less than in a commutator type meter, because of the absence of a commutator and an armature. On the other hand, the torque is less so that the effect of friction at light load still has to be compensated. The principle employed in practically all meters is that in which a flux is produced at the potential pole face, slightly out of phase with the main flux. Thus, eddy currents will be produced in the disk which will be in phase with a small component of the main flux, giving rise to a slight torque which can be made sufficient to overcome the friction torque. This "out-of-phase" flux is produced in various ways in different meters. A common method is to place a short-circuited copper circuit or thin copper punching ("shading-strip") in the potential-pole air gap, in an unsymmetrical position, so that the desired unbalanced flux will be obtained.

6.33 Meters for Polyphase Circuits—To facilitate metering, watt-hour meters for commercial use are made in various forms in addition to the simple single-phase form. Among these are three-wire meters for three-wire, single-phase circuits, polyphase 2-element meters for three-wire, two-phase or three-phase circuits; polyphase 2-element and 3-element meters for

four-wire, three-phase circuits, etc. Portable standard watt-hour meters are usually available only in the single-phase form. Hence for testing purposes poly-phase circuits are usually metered by connecting standards into the circuit in exactly the same manner as wattmeters. The use of single-phase meters has the advantage of giving further data such as balance of load and average power factor, and the correction for instrument-transformer errors can be made more accurately and directly.

6.40 Application of Service Meters and Standard Meters—The regular service type of meter is applicable in a test which extends over a long time and where the change in the register readings is sufficiently great so that the observational errors are reduced to a permissible percentage of the difference between the readings. For example, if the register can be read to only 1 kwhr, and the difference between the initial and final readings is 100 kwhr, the observational error would be one percent—an error which would be permissible where only approximate results were desired.

In general, watt-hour meters of the regular service type, with standard registers do not permit of sufficiently precise readings for plant tests. However, such meters can be supplied with special registers which have additional dials reading down to 0.01 kwhr in the case of 5 ampere, 110 volt meters. With these registers the accuracy of reading is very much higher, and is adequate in cases where the test is continued for a period of several hours. In standard watt-hour meters, the revolutions of the rotating element are registered directly, and the number of revolutions multiplied by the watt-hours per revolution gives the energy which has passed through the meter in the elapsed time. Such meters can be read to a high degree of accuracy, but at rated load the register reading repeats every few minutes, making it necessary, in long runs, to keep a tally of the number of repeats.

The ordinary service type of meter may be used in a similar manner by disregarding the register and counting the revolutions of the disk by direct observation. The disk may be marked off in quarters or tenths to get the necessary accuracy with a small number of revolutions.

When the average power is required the elapsed time must be accurately determined. The meter should be allowed to run continuously, and the exact time for a definite number of revolutions may be determined with a stop-watch reading to fractions of a second, if the interval is short, or an ordinary watch reading seconds, for longer intervals. The important point is to observe both revolutions and time with sufficient precision to keep the observational error small, preferably 0.2 percent or less.

6.50 Range and Accuracy—See paragraph 1.40 and 141.

6.60 Precautions in Taking Readings—See paragraph 1.60.

6.61 Rating—The rating of the meter should be such that it will operate at loads well removed from either the light-load or the overload part of the curve. In the former the effects of variable friction are a possible source of inaccuracy, and at heavy overloads the accuracy changes appreciably with change of load. In general, the region between half load and full load is to be preferred.

6.62 Location—The meter should be on a table or other support, which is free from vibration and which is level.

6.63 Temperature—The meter should be in the circuit sufficiently long before readings are taken to insure uniform and constant temperature throughout. This is ordinarily not less than one-half hour. When ordinary service meters are used for testing purposes, the cover should be left on to insure uniform temperature and also to eliminate the effects of air drafts, dust, etc., a special aperture being provided, if necessary, to view the rotating disk.

6.64 Stray Fields—Direct-current meters are readily affected by external magnetic fields since they contain no iron and the field strength is, therefore, low. Care should be taken that such meters are not located where the stray field from conductors carrying current can introduce errors. Even the very low value of the earth's magnetic field is sufficient to introduce errors at light loads. The best procedure is to test such meters in the laboratory with the plane of the field coils parallel to the direction of the local field, as determined by placing a magnetic compass at the spot before the meter is brought to it and to locate the meter in the same way during its use for plant tests. The direction of the local field should not be assumed to be north and south, because it is likely to be different as a result of local conditions, such as the presence of structural iron work. The correctness of location of the meter may be checked by noting whether it rotates on voltage only. If it does, it should be oriented until rotation ceases. This statement assumes that the light-load adjustment is correctly made. The meter should be kept well away from direct-current instruments of the permanent-magnet type, magnetos, telephones, etc., preferably two feet or more. Alternating-current meters also will be affected by intense alternating magnetic fields. The best procedure is to check the meters after installation in the place in which they are to be used.

6.65 Meter Adjustments—The speed of both commutator and mercury-motor direct-current meters is adjusted principally by shifting the drag magnets diametrically with respect to the meter shaft, thus altering the retarding torque. The retarding torque is a

minimum when the magnets are close to the shaft and a maximum when they are near the edge of the disk. In some meters, a micrometer adjustment is provided for making small changes in speed. It consists of a movable piece of soft steel or a steel screw which bridges the gap between the magnets, and shunts more or less of the flux from the drag disk. Any change in the magnets produces the same percentage effect at all speeds so that the accuracy curve is merely shifted parallel to itself.

In addition to the magnet adjustments which affect all loads equally, the speed at light load (10 percent or less) is adjusted independently by the methods previously described (paragraph 6.32). The effect of these compensating devices is substantially inversely proportional to the load, that is, the effect at 5 percent load is twice that at 10 percent load.

In induction type meters convenient means are usually provided for adjusting the meter speed at light load and full load. The position of the light-load compensation coil or plate can be changed by means of conveniently located screws and the light-load speed thus altered. Speed adjustment at the higher loads is obtained by shifting the drag magnets with respect to the axis, as in direct-current meters, or by shunting the flux by means of a movable soft-iron keeper bridging the air gap. The power factor or lag adjustment is made at the factory and if properly done should never require readjustment, in most modern single-phase meters. In polyphase meters careful adjustment is required for accurate results.

6.70 Corrections for Current and Potential Transformers—Current and potential transformers are used with watthour meters just as with wattmeters when the current and voltage exceed moderate values. See under INSTRUMENT TRANSFORMERS and POWER MEASUREMENTS, for corrections when using instrument transformers.

The amount of the error corresponding to various phase angles and power factors is given in the tables under POWER MEASUREMENTS (angle α in the first column is neglected because any error due to it is taken care of if the meter has been calibrated at the power factor obtaining in use).

In the case of potential transformers, the voltage and the volt-ampere burden connected to the secondary are practically constant. Consequently, the correctable errors are constant and can be compensated for by means of the regular load adjustments on the watthour meter. In current transformers, the connected load or burden is also constant but both the ratio and phase-angle errors vary with the current. However, these errors are generally small and adequate accuracy can usually be secured by compensating for the error corresponding to average load conditions by means of the load adjustments of the meter.

When a balanced three-phase load is measured with a two-element polyphase watthour meter, and the ratio and phase-angle characteristics of the transformers used with the two elements are identical, the error can be computed on a single-phase basis. The power factor of the load can be conveniently found from the ratio of the revolutions per minute of the disk, first with one element alone, then with the other element alone. From this ratio, the apparent power factor of the load corresponding to the secondary currents and voltages, $\cos \theta_s$, may be computed from the formulas given in paragraph 8.31 where W_1 denotes the greater value of revolutions per minute, and W_2 the lesser. The true power factor of the load, $\cos \theta$, is then $\cos (\theta_s + \beta + \gamma)$ as in the single-phase case, α being omitted on the assumption that it is zero, i.e., that the lag adjustment of the meter is correct; the procedure to be followed to get the true primary energy is then identical with that explained in paragraph 5.85 for single-phase power. The discussion in paragraph 5.85 of the relative errors in the two elements of a polyphase wattmeter applies to the polyphase watthour meter as well, and thus, similarly in multi-element watthour meters it is advisable to correct the part of the registration due to each element separately, since balanced loads are only approximately realized in practice.

6.80 Calibration of Watthour Meters — Watthour meters for engineering tests are customarily calibrated by determining the percentage registration, that is, the percentage of the energy passed through the meter which is registered on the meter register. The watthours registered in a given time are noted while the average power is simultaneously measured during the same period with standard instruments. Because of the time required to get an accurate reading from the register, it is customary to use the revolutions of the rotating element in a given short period of time instead of the register indications. Since the energy represented by one revolution, or the watt-hour constant, has been assigned by the manufacturer and marked usually on the nameplate, the watthours registered by the meter in a given period will be $K_h \times R$, where K_h is the watt-hour constant and R is the number of revolutions. The accuracy of the gear ratio between the rotating element and the first dial of the register can be determined by count.

The percent registration is then readily computed. Thus,

$$\begin{aligned} \text{Percent registration} &= \frac{\text{meter watthours}}{\text{true watthours}} \times 100 \\ &= \frac{K_h \times 3600 \times R}{S \times W} \times 100 \end{aligned}$$

where K_h = watt-hour constant, 3600 = number of seconds in 1 hour, R = revolutions in the test

period of S seconds, and W = true average power in watts during the test period as measured with indicating instruments. The last formula is the standard formula used in testing watthour meters.

The constant marked on the nameplate by some manufacturers may be other than the watthour constant. This should always be checked before proceeding with the calibration. Very complete information regarding meter constants and other meter data, may be found in the "Electrical Metermen's Handbook" published by the Edison Electric Institute, New York, N. Y. The current edition is the sixth, published in 1950.

6.81 Source of Energy—The source of energy for meter testing should be as steady as possible. The testing load may be banks of lamps or rheostats, in series with which the meter and the standard instruments are connected. A preferable method is to separate the current and potential circuits and connect them to independent sources, the former being a relatively large-current, low-voltage source and the latter a high-voltage, low-current source. Conditions are more easily adjusted by this method and with large meters, a saving of energy is effected.

6.82 Correct Measurement of Energy—The correct measurement of the energy which passes through the meter involves the accurate measurement of power in watts and of time in seconds.

In calibrating direct-current meters for testing purposes, the power is obtained by measuring the voltage and the current, preferably with a potentiometer or with instruments of the laboratory standard type.

In calibrating alternating-current meters, laboratory standard indicating wattmeters are used to measure the power. While the power could be obtained from the current and the voltage as measured with a voltmeter and ammeter, respectively, this method could be used only at unity power factor and is not as accurate.

Testing of a service meter by comparison with a standard meter involves no exact determination of time since it consists only in comparing the number of revolutions of the two meters for identical duration of the same load. But the original verification of the standard meter does involve accurate determination of the time during which a constant and accurately known load is allowed to cause rotation of the meter. For many years the stopwatch was used for this purpose but its accuracy is considerably inferior to (1) clocks with contacts carried on the pendulum or (2) clocks with photocell beams intercepted by the pendulum or (3) tuning-fork-controlled clocks or (4) 100,000-cycle quartz crystal oscillators with 1000-cycle accessories. Any of the above methods can be used to control accurately the starting and stopping of a standard meter during calibration.

6.83 Power-Factor Variation—One of the most convenient methods of obtaining power-factor variation for meter testing is provided through the use of a phase shifter, one form of which, known as a rotatable phase-adjusting transformer is similar to a three-phase induction motor. The wire-wound rotor of this device can be moved to any position through 360 electrical degrees by means of a worm-gear handwheel. In this way a single-phase voltage or the three-phase voltages induced in the rotor with three-phase voltages applied to the stator may be made to take any desired time phase position. The primary terminals of the phase-adjusting transformer are connected to a three-phase supply and the potential circuit of the meter under test is connected to the secondary terminals. The current coils of the meter are connected through a suitable current-control device to the same circuit to which the primary terminals of the phase shifter are connected.

Similar phase shifting devices are also made for two-phase operation. Either the two-phase or the three-phase type can be used in tests of single-phase meters.

6.84 Polyphase Meters—These meters are usually tested as single-phase meters by connecting the current circuits in series and the potential circuits in parallel. It should be first determined, however, that the elements are equal in accuracy by testing each separately, and also that there is no interference between the two elements, that is, no stray field from one element which affects the accuracy of the other element. In testing the elements separately, it is necessary to have both voltage circuits energized, because in the normal use of the meter a part of the damping torque is due to the action of the two voltage fluxes.

A test for independence of elements can be made by connecting one element to phase I of a two-phase circuit. With first 20 percent and then 100 percent rated current in this element (at unity power factor), the other element is successively connected to phase I as follows:

- (a) current circuit not connected, voltage circuit connected direct and then reversed;
- (b) voltage circuit not connected, current circuit connected direct and then reversed;
- (c) repeat, connecting to phase II instead of phase I. It will be observed that under these various conditions the maximum effect of any stray field from the current or voltage circuit of one element will be obtained in the second element because the stray field will be in phase with one or the other of the two fields in the second element.

A test for balance of elements is made by connecting as a single-phase meter but with current

in one element reversed. If balanced, the rotating element will stand still. If unbalanced, it will run backward, or forward depending on which series field is the stronger. An adjustment is usually provided for correcting unbalance, either by changing the reluctance of the path of the flux from one of the current electromagnets, or by shifting one of the current electromagnets radially with respect to the disk.

FREQUENCY MEASUREMENTS

- 7.10 Description**—The frequency of an alternating current is the number of complete cycles per second, or the number of alternations per second divided by two. For the ordinary alternator, the frequency is

$$f = \frac{pn}{2}$$

where f = frequency in cycles per second, p = number of poles on the field of the generator and n = revolutions per second.

When the generator is readily accessible, often the simplest way to determine the frequency is to note the number of poles on the generator and measure its speed. The frequency can also be measured by means of instruments which are connected directly to the circuit. They have the additional advantage that, being indicating instruments, the frequency is shown at every instant. There are three principal types—mechanical resonance or vibrating-reed type, moving-coil type, and moving-vane type.

- 7.20 Vibrating-Reed Frequency Meter**—A row of narrow strips of steel of varying lengths, attached at one end to a common support and with the other end free to move, is located in the field of an electromagnet which is energized from the circuit under observation. The strips have different natural periods and the one with a period most closely corresponding to the alternations of the magnetic field (and, therefore, the circuit to which it is connected) will be set in vibration. The reeds are horizontal with the ends turned up and painted white so that when a particular reed vibrates, a white band is formed. The fine adjustment of the period of each reed is obtained by adding a minute weight at the end.
- 7.21 Moving-Vane Frequency Meter**—This type is shown in figure 7.21-1 where 1,1 and 2,2 are fixed coils, 90 degrees apart, and c,c is the movable element consisting of a soft-iron core mounted on a shaft, with no control of any kind. Coil 2,2 is connected in series with a non-inductive resistance R_1 , and coil 1,1, in series with an inductance X_1 . A second non-inductive resistance R_1 is connected in parallel with 1,1 and X_1 . A second inductance, X_2 is connec-

ted in parallel with 2,2 and R_2 . The soft-iron core takes up the position of the resultant field produced by the two coils. When the frequency increases, the current decreases in 1,1 and increases in 2,2, thus shifting the direction of the resultant field and the position of c,c to which the pointer is attached. The opposite effect takes place when the frequency is decreased. The series inductance X serves merely to damp the higher harmonics which are present if the voltage wave shape is distorted.

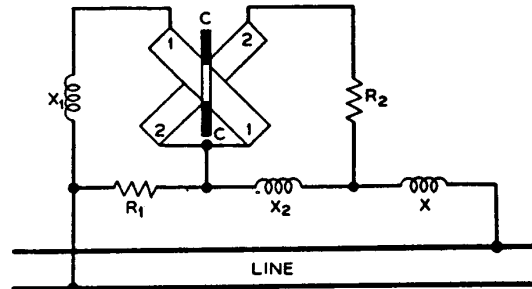


Fig. 7.21-1 Circuit of the moving-vane frequency meter.

- 7.22 Moving-Coil Frequency Meter**—This type is similar to the moving-vane type except that two coils rigidly fastened together form the moving system and a single fixed coil is the stationary member.

- 7.23 Measurement of High Frequencies**—Where great accuracy is not required, measurement of high frequencies can be made with a wave or frequency meter shown diagrammatically in figure 7.23-1. The RLC circuit equipped with some indicating device is loosely coupled to the circuit, the frequency of which is to be measured.

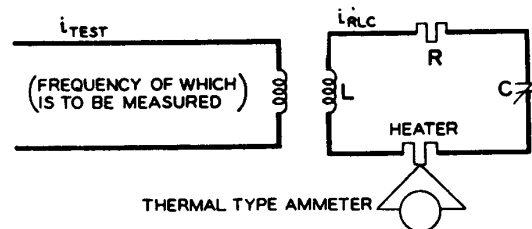


Fig. 7.23-1 Wave meter method of measuring high frequencies.

Maximum current is first obtained by proper adjustment of L or C . Theoretically, the resonant frequency can be calculated from the circuit parameters which yield maximum current, but usually the device is calibrated against some form of standard frequency meter. The frequency which is to be measured is then determined by reference to a calibration chart for the particular values of L and C employed to give maximum current in the RLC loop. The device depends upon being sufficiently loosely coupled so that no appreciable reaction in

the test circuit results from the current in the *RLC* loop.

High frequencies can also be measured either directly by means of a cathode-ray oscillograph with calibrated time basis or by means of comparison with the frequencies standard using Lissajous Figures.

7.24 Relative Advantages—Frequency meters of the moving-vane and moving-coil types, being pointer instruments, give a continuous indication of the frequency which is easily interpolated, while the reed type gives indications corresponding primarily to certain fixed values, say one-fourth or one-half cycles apart. However, the pointer instruments are appreciably affected by waveform changes, while the reed type is only very slightly affected; furthermore with a little practice one can interpolate readily to half-intervals on a reed type frequency meter, or even more closely if the frequency changes slowly and the initial calibration adjustment of the individual reeds has been carefully performed. Pointer type frequency meters are especially suitable for switchboard use, while the reed type is preferable for checking switchboard frequency meters and for laboratory use because it is practically independent of wave form and has a low temperature coefficient (0.01 percent per degree C).

7.30 Range and Accuracy—See paragraphs 1.40 and 1.41.

7.40 Calibration—Frequency meters are calibrated by connecting them to a small alternator, the speed of which can be kept steady over a range of values, and then accurately measuring the speed. The voltage applied to the instrument should be approximately the same as that in the test and it should be applied to the instrument long enough to heat it to the operating temperature, unless the instrument is for intermittent use only, in which case the voltage is applied only long enough to secure a reading. In general, high accuracy of frequency measurements is not required in power tests.

POWER FACTOR MEASUREMENTS

8.10 Description—The power factor of a circuit is the ratio of the true power in watts, as measured with a wattmeter, to the apparent power obtained from the product of the current and the potential, in amperes and volts, respectively. In the ordinary continuous-current circuits, the power factor is obviously unity, but with pulsating currents, such as occur in rectifier circuits, for example, it may be slightly less than unity. In alternating-current circuits, the power factor is usually less than unity, because the current and the potential are not in phase. When the wave form is sinusoidal (and only

then), the power factor is also equal to the cosine of the phase angle.

8.11 Power-Factor Determination—The general practice in testing alternating-current electric equipment is to compute the power factor from the various electrical quantities which are being measured for other parts of the test. Usually it is not necessary to determine the power factor with extreme accuracy or very frequently during a test. When, however, frequent observations of the power factor are required, calibrated instruments which indicate the power factor directly may be used.

8.12 Types of Power-Factor Meters—The two most generally used types of power-factor meters are those employing a moving coil or coils and those having a moving soft-iron vane.

8.13 Moving-Coil Type Instruments—The principle of operation of the single-phase instrument is shown in figure 8.13-1. The arrangement is similar to that in wattmeters, except that there are two coils, *M, M'*, in the moving system instead of one. One coil, *M*, is connected across the line and in series with a resistance, *R*, while the other coil, *M'* is connected in series with an inductance, *L*. The current in the coil *M'*, will, therefore, be about 90 degrees out of phase with that in coil *M*. When the power factor is unity, the reaction between the fixed coils, *F', F* and the moving coil, *M*, will be a maximum, while that between *F', F*, and *M'* will be a minimum. The torque exerted on *M* will cause the moving system to take the position of minimum torque, that is, where the plane of *M* will be parallel to that of *F' and F*; the corresponding mark on the scale will, therefore, be 100. Similarly, at zero power factor, coil *M'* will exert all of the torque and cause the moving system to take a position where the plane of *M'* will be parallel to that of *F' and F*; the corresponding indication is therefore zero. Theoretically, the indications will be affected by the frequency because the current in *L* depends upon the frequency, but by proper design of the inductance *L*, the effect of moderate variations in

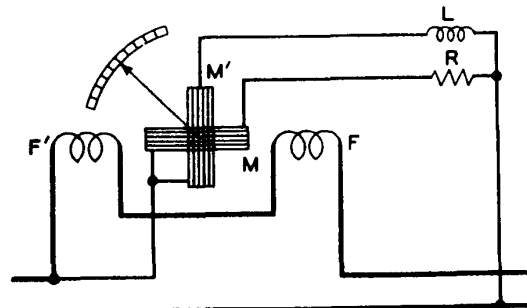


Fig. 8.13-1 Illustrating principle of moving-coil type of power-factor meter for single-phase circuits

frequency can be eliminated. Commercial instruments are substantially correct for a deviation from the calibration frequency of about ± 5 cps.

In the polyphase meter, which is accurate only for balanced circuits, the inductance, L , is replaced by a resistor, R . The two coils in the moving system are connected in Y across the three phases. The principle of operation is exactly the same as in the single-phase instrument, the moving system taking a position where the resultant torque is zero, which position varies with the phase of the current in the current coil.

8.14 Moving-Iron-Vane Instruments—This type has a movable soft-iron vane which is magnetized by means of a fixed coil carrying the current in one phase of the circuit. In the polyphase form there is one voltage coil for each phase so that a rotating field is obtained. The vane takes up a position in which the direction of the flux produced in it by the current coil when at a maximum is coincident with the direction of the resultant flux due to the voltage coils. For three-phase circuits, three voltage coils are used, placed 120 degrees apart, and for two-phase circuits two coils are used, placed 90 degrees apart. For single-phase circuits, the rotating field is obtained with two voltage coils placed 90 degrees apart, one being connected to the circuit through a non-inductive resistor and the other being connected to the same line through an inductor.

8.15 Volt-Ampere Meters—If the "apparent" power, or total volt-amperes, could be obtained as the reading of an indicating instrument the power factor could be secured simply by dividing the reading of the wattmeter by the reading of the volt-ampere meter. Volt-ampere meters are made in which the desired product of voltage and current is produced (a) by bringing a flux derived from the line current into phase with the current in a coil connected to the line voltage or (b) by shifting the phase of the "voltage" current until it is in phase with the line current. The resulting torque is proportional to the product of the two quantities and the result is indicated by movement of a pointer over a graduated scale.

The total volt-amperes, VA, can be computed from the power or "active" volt-amperes, W , and the reactive volt-amperes, VAR.

$$VA = \sqrt{W^2 + (VAR)^2}$$

The power factor is then readily computed from the relation,

$$\cos \theta = \frac{W}{VA}$$

8.16 Reactive Volt-Ampere Meters or Varmeters—Reactive volt-ampere meters are instruments which indicate the product of the voltage, current, and

sine of the phase angle between the voltage and current in the circuit. The reactive volt-amperes, VAR equal $E I \sin \theta$. For single-phase circuits, the current in the potential coil of a wattmeter may be displaced in phase from the applied voltage by nearly or exactly 90 degrees, by use of a series capacitor and parallel-inductor arrangement in place of the usual series resistor. For two-phase circuits, the wattmeters of figures 5.52-1 and 5.53-1 will indicate the total reactive volt-amperes if the connections of their voltage elements to the two phases are interchanged. For three-phase, three-wire circuits a two-element wattmeter may be used with two phasing transformers. The two phasing transformers are used to shift the phases of the two potentials applied to the potential coils of the meter and to change the magnitude of these potentials so that the instrument readings may be used directly without the use of multiplying factors (Source: *Alternating-Current Circuits* — Bryant, Correll, Johnson 1939). The accuracy of all methods of measuring reactive volt-amperes in polyphase systems by the use of phasing transformers or interchanged phase connections depends on balanced line voltages. In general, line voltages are sufficiently well balanced to give satisfactory results. Reactive volt-ampere meters usually have the zero point at the center of the scale.

8.20 Range and Accuracy—See paragraph 1.40 and 1.41.

8.30 Power Factor of Single-Phase Circuits—The power factor of single-phase circuits is the ratio of watts to volt-amperes.

8.31 Power Factor of Polyphase Circuits—The power factor of polyphase circuits which are balanced is the same as that of the individual phases. When the phases are not balanced, several differing alternative kinds of "power factor" can be defined.

The power factor of a balanced two-phase, three-wire circuit is obtained by the two-wattmeter method from the relation $W_2/W_1 = \tan \theta$, where W_1 is the reading of a wattmeter with its current coil connected in one phase (outside wire) in the same manner as in a single-phase circuit, and W_2 is the reading of a second wattmeter connected with its current coil in the first phase, in series with that of the first wattmeter, and the voltage coil is connected between the other outside wire and the neutral. Obviously, if the load is steady, one wattmeter can be used for both readings.

In a three-phase, three-wire balanced circuit the two wattmeters are connected as for measuring power. The power factor is calculated from the two values of power indicated by the two instruments by any of the following formulas or other formulas which may be derived therefrom:

$$\cos \theta = \frac{1}{\sqrt{1 + 3 \left(\frac{W_1 - W_2}{W_1 + W_2} \right)^2}} \quad (1)$$

$$\tan \theta = \sqrt{3} \left(\frac{W_1 - W_2}{W_1 + W_2} \right) \quad (2)$$

$$\cos \theta = \frac{1 + \frac{W_2}{W_1}}{2 \sqrt{1 + \left(\frac{W_2}{W_1} \right)^2 - \frac{W_2}{W_1}}} \quad (3)$$

Where W_1 = watts indicated by the instrument measuring the larger amount of power which is always positive and W_2 = watts indicated by the instrument measuring the smaller amount of power which may be either positive or negative. In the case of the second formula the power factor, $\cos \theta$, is of course obtained from a table of natural functions.

Where frequent calculations of the power factor in balanced three-phase circuits are to be made, the curve in figure 8.31-1 may be found convenient. It gives the power factor directly for any value of the ratio of W_2 (smaller watts) to W_1 (larger watts). The principal coordinates are as follows:

Ratio, $\frac{W_2}{W_1}$	Power Factor
-1.0	0
-0.8	0.064
-0.6	0.143
-0.4	0.240
-0.2	0.359
0.0	0.5
+0.2	0.655
+0.4	0.803
+0.6	0.918
+0.8	0.982
+1.0	1.0

8.32 Power Factor of Rectifying Units—The power factor of a rectifier unit can be determined from tests by measuring the watts and volt-amperes at the a-c line terminals or calculated from the characteristics of the rectifier and transformer equipment as specified in American Standard C34.1-1949. The power factor determined by measurement is likely to differ from the calculated value because of the a-c system reactance which effects the wave shape of the alternating current and voltage. In general,

the power factor of a rectifier unit cannot be measured directly by means of a power-factor meter and cannot be determined from measurements with a wattmeter and a reactive volt-ampere meter, because these instruments are responsive to interaction between currents and voltages of the same frequency and will not include the effects of harmonic components in the current. Measurements with these instruments will give the displacement factor only. For a rectifier unit, or a group of rectifier units, with a total of 24 phases or more, the rms value of the alternating line current is practically the same as the rms value of its fundamental component, and the power factor approaches closely the value of the displacement factor. The power factor of such a circuit can, therefore, be measured with these instruments with negligible error.

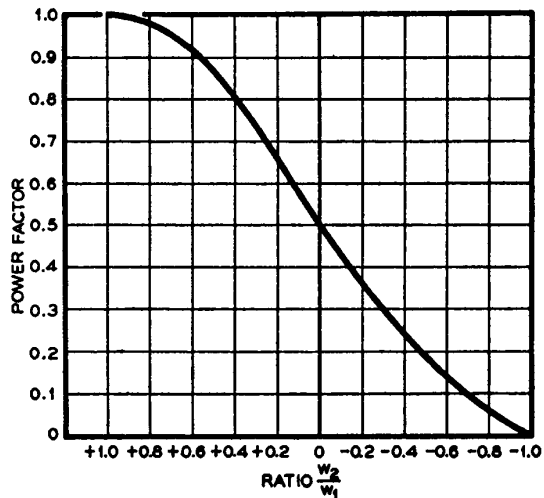


Fig. 8.31-1 Power Factor Curve

8.40 Precautions in Taking Readings—Attention is called to the necessity for noting the sign of W_2 . For power factors less than 0.5, W_2 will be negative and the ratio, W_2/W_1 , will be negative. When it is not certain whether the power factor is greater or less than 0.5, a test can be made as follows.

Change the potential connection of each instrument from the middle wire (the one in which there is no wattmeter current coil) to the other outside wire and note the indication. If the power factor is over 50 percent, the new indication of each instrument will be in the same direction as the original indication. If the power factor is less than 50 percent, both new indications will be reversed from the original indications.

8.50 Calibration—The proper calibration of power factor meters involves the use of apparatus and facilities

which are not ordinarily available outside a well-equipped electrical testing laboratory. Power factor meters should, therefore, be sent to such a laboratory for calibration or be returned to the manufacturer.

IMPEDANCE MEASUREMENTS

9.10 Description—The effective magnitude of the impedance, Z , of a circuit depends upon the circuit parameters, R (resistance), L (inductance or self-inductance), M (mutual-inductance), and C (capacitance). The effective magnitude of these parameters is often influenced by temperature, frequency, potential gradient, current density, magnetic density, etc. The impedance of a circuit should, therefore, be measured under conditions which are as nearly identical to actual operating conditions as possible.

9.11 Determination of Impedance—The impedance of high power circuit elements can be evaluated directly from experimentally determined values of voltage, current, and power, after applying corrections for errors introduced by the insertion of the instruments in the circuit.

In making either voltage or current corrections, due consideration must be given to the vector relations of the quantities involved. If the wattmeter potential circuit and the voltmeter are connected on the load side of an uncompensated wattmeter current coil, as shown in figure 9.11-1, the V^2/R loss in the potential circuits must be subtracted directly from the wattmeter reading to obtain the correct power absorbed by the load.

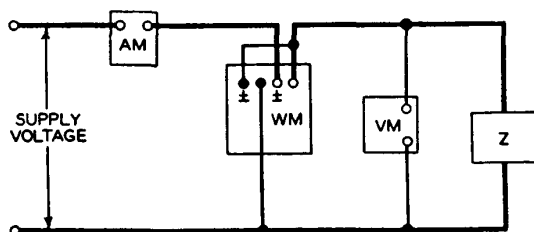


Fig. 9.11-1 Method of determining the impedance.

9.12 Effective Resistance—The effective resistance of a circuit is defined as the ratio of the power to the square of the current in the load.

$$R_e = \frac{W}{I^2}$$

For example, the effective resistance of the load impedance shown in figure 9.11-1 can be determined directly from the corrected readings of the ammeter and wattmeter. R_e as found from the above equation may differ materially from the ohmic or d-c resistance. This is due to any or all of the following effects; skin effect, electromagnetic or electrostatic

coupling with other circuits, or the proximity of magnetic or dielectric material.

9.13 Effective Reactance—The effective or equivalent series circuit reactance of a network or circuit is defined as:

$$X_e = \sqrt{Z_e^2 - R_e^2}$$

The magnitude of X_e can be evaluated from the above equation after having determined Z_e , effective impedance, and R_e , effective resistance, from physical measurements of voltage, current, and power.

The reactance of a circuit may be inductive or capacitive depending on the magnitude of the various circuit parameters.

9.14 Inductance—The self-inductance, or coefficient of self-induction, of a circuit is the constant by which the time rate of change of the current in the circuit must be multiplied to give the self-induced counter emf. Similarly, the mutual inductance between two circuits is the constant by which the time rate of change of current in either circuit must be multiplied to give the emf thereby induced in the other circuit. Self-inductance and mutual inductance depend upon the shape and dimensions of the circuits, the number of turns and the nature of the surrounding medium.

9.15 Standards of Inductance—Primary standards of inductance are usually single-layer coils of copper wire wound with great care on non-conducting, non-magnetic cores which will not change in dimensions with time or with variations in temperature and humidity. The inductance is computed from the number of turns and the dimensions of the coil. Working standards of inductance are usually multiple-layer coils wound on cores or frames of seasoned wood, bakelite or marble, and standardized by comparison with primary standards.

9.16 Capacitance—The electrostatic capacitance of two conductors separated by a dielectric is measured by the electrostatic flux which is stored in the dielectric when a given potential difference is maintained between the conductors, which flux in turn depends upon the surface area of the conductors, the distance between them, the character of the dielectric, and, to some extent, on the temperature and the pressure.

9.17 Standards of Capacitance—Primary standards are made with air as the dielectric and in which the effect of absorption and leakage is made nil by providing alternate plates with guard rings which receive the unavoidable absorption and leakage currents in the insulation required for mounting the plates. Commercial standards are made with tin foil and high-grade mica, bound together under high pressure.

9.20 Difficulties Encountered in Making Measurements—In many cases it is practically impossible to

measure circuit parameters, R , L , M , and C by means of the voltmeter-ammeter-wattmeter method. In low-power circuit elements the allowable current may be too small to operate successfully a normal wattmeter or ammeter. In other cases the circuit may be so radically disturbed as a result of the introduction of instruments that the measurements made are useless insofar as original circuit parameter determination is concerned. Vacuum tube devices which are sometimes employed to measure voltage, current, and power draw very little or no power from the circuit which is under investigation, and for this reason they are useful adjuncts to normal, metering equipment in certain cases. However, vacuum tube meters are very limited in range, and the results obtained are subject to several sources of inaccuracy.

- 9.30 Bridge Methods**—Bridge methods are generally to be preferred in making measurements involving low-power circuit elements. This is particularly true if the effective values of the parameters are to be determined at frequencies ranging from 100 to 2500 cps.

Alternating-current bridges which take the same general form as the familiar d-c Wheatstone bridge are very widely used to measure inductance, both mutual and self-inductance, and capacitance. A simple form of a-c bridge is shown in figure 9.30-1. Many of the bridges employed in practice contain two resistance arms and two impedance arms. For best results the two resistance arms are accurately calibrated resistances which are wound so as to reduce self-inductance and self-capacitance effects. To obtain greatest flexibility the resistance arms are adjustable, but for certain operating conditions they may take the form of fixed resistances. The other two arms of the bridge are the impedance arms: one, the standard impedance ($R_s + jX_s$); the other, the unknown impedance ($R_x + jX_x$) which is to be measured.

After adjustments of R_c , R_d , R_s , and X_s have been made so that no potential difference exists between points c and d, then:

$$R_x = \frac{R_c}{R_d} R_s$$

and

$$X_x = \frac{R_c}{R_d} X_s$$

This last equation shows that, if the unknown impedance is inductive in character, the standard impedance must also be inductive in character. If the unknown impedance is capacitive in character,

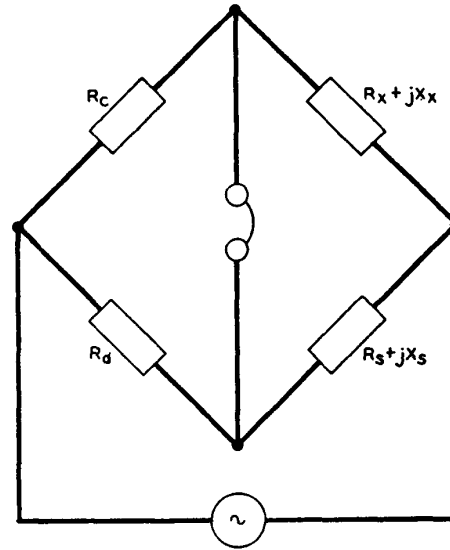


Fig. 9.30-1 Similar-angled bridge

then the standard impedance must also be capacitive in character provided that the arms are arranged as shown in figure 9.30-1.

If the reactive element of the unknown impedance is opposite in nature to the reactive element of the standard impedance, then the bridge arms R_c and $R_s + jX_s$ must be interchanged. Bridges of this general class are called opposite-angle bridges.

- 9.31 Detectors Used in Bridge Methods**—Detectors used in bridge measurements of inductance and capacitance are selected according to the test frequency and the impedances being compared. The vibration galvanometer is usually satisfactory at commercial power frequencies for relatively low impedance bridges; the frequency of the source must be constant and of the value to which the galvanometer is adjusted. For bridge measurements at both power and audio frequencies a cathode-ray null detector of adequate sensitivity or an indicating meter connected to the output of a vacuum tube amplifier can be used.

RESISTANCE MEASUREMENTS

- 10.10 Description**—The various methods of measuring resistance and the application of these methods in determining the performance of electric machines is covered by the AIEE Master Test Code for Resistance Measurements, No. 550.

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